

Chapter 4

Source Characterization

Robert Pitt

The Source Concept

Urban runoff is comprised of many separate source area flow components that are combined within the drainage area and at the outfall before entering the receiving water. Considering the combined outfall conditions alone may be adequate when evaluating the long term, area-wide effects of many separate outfall discharges to a receiving water. However, if better predictions of outfall characteristics (or the effects of source area controls) are needed, then the separate source area components must be characterized. The discharge at the outfall is made up of a mixture of contributions from different source areas. The “mix” depends on the characteristics of the drainage area and the specific rain event. The effectiveness of source area controls is, therefore, highly site and storm specific.

Various urban source areas all contribute different quantities of runoff and pollutants, depending on their characteristics. Impervious source areas may contribute most of the runoff during small rain events. Examples of these source areas include paved parking lots, streets, driveways, roofs, and sidewalks. Pervious source areas become important contributors for larger rain events. These pervious source areas include gardens, lawns, bare ground, unpaved parking areas and driveways, and undeveloped areas. The relative importance of the individual sources is a function of their areas, their pollutant washoff potentials, and the rain characteristics.

The washoff of debris and soil during a rain is dependent on the energy of the rain and the properties of the material. Pollutants are also removed from source areas by winds, litter pickup, or other cleanup activities. The runoff and pollutants from the source areas flow directly into the drainage system, onto impervious areas that are directly connected to the drainage system, or onto pervious areas that will attenuate some of the flows and pollutants, before they discharge to the drainage system.

Sources of pollutants on paved areas include on-site particulate storage that cannot be removed by usual processes such as rain, wind, and street cleaning. Atmospheric deposition, deposition from activities on these paved surfaces (e.g., auto traffic, material storage) and the erosion of material from upland areas that directly discharge flows onto these areas, are the major sources of pollutants to the paved areas. Pervious areas contribute pollutants mainly through erosion processes where the rain energy dislodges soil from between vegetation. The runoff from these source areas enters the storm drainage system where sedimentation in catchbasins or in the sewerage may affect their ultimate discharge to the outfall. In-stream physical, biological, and chemical processes affect the pollutants after they are discharged to the ultimate receiving water.

Knowing when the different source areas become “active” (when runoff initiates from the area, carrying pollutants to the drainage system) is critical. If pervious source areas are not contributing runoff or pollutants, then the prediction of urban runoff quality is greatly simplified. The mechanisms of washoff and delivery yields of runoff and pollutants from paved areas are much better known than from pervious urban areas (Novotny and Chesters 1981). In many cases, pervious areas are not active except during rain events greater than at least five or ten mm. For smaller rain depths, almost all of the runoff and pollutants originate from impervious surfaces (Pitt 1987). However, in many urban areas, pervious areas may contribute the majority of the runoff, and some pollutants, when rain depths are greater than about 20 mm. The actual importance of the different source areas is highly dependent on the specific land use and rainfall patterns. Obviously, in areas having relatively low-density development, especially where moderate and large sized rains occur frequently (such as in the Southeast), pervious areas typically dominate outfall discharges. In contrast, in areas having significant paved areas, especially where most rains are relatively small (such as in the arid west), the impervious areas dominate outfall discharges. The effectiveness of different source controls is, therefore, quite different for different land uses and climatic patterns.

If the number of events exceeding a water quality objective are important, then the small rain events are of most concern. Stormwater runoff typically exceeds some water quality standards for practically every rain event (especially for bacteria and some heavy metals). In the upper midwest, the median rain depth is about six mm, while in the southeast, the median rain depth is about twice this depth. For these small rain depths and for most urban land uses, directly connected paved areas usually contribute most of the runoff and pollutants. However, if annual mass discharges are more important (e.g. for long-term effects), then the moderate rains are more important. Rains from about 10 to 50 mm produce most of the annual runoff volume in many areas of the U.S. Runoff from both impervious and pervious areas can be very important for these rains. The largest rains (greater than 100 mm) are relatively rare and do not contribute significant amounts of runoff pollutants during normal years, but are very important for drainage design. The specific source areas that are most important (and controllable) for these different conditions vary widely.

This chapter describes sources of urban runoff flows and pollutants based on many studies as found in the literature. This chapter also reports on the specific source area sampling activities conducted as part of this research funded by the USEPA for use in this report.

Sources and Characteristics of Urban Runoff Pollutants

Years of study reveal that the vast majority of stormwater toxicants and much of the conventional pollutants are associated with automobile use and maintenance activities and that these pollutants are strongly associated with the particulates suspended in the stormwater (the non-filterable components or suspended solids). Reducing or modifying automobile use to reduce the use of these compounds, has been difficult with the notable exception of the phasing out of leaded gasoline. Current activities,

concentrated in the San Francisco, CA area, focus on encouraging brake pad manufacturers to reduce the use of copper.

The effectiveness of most stormwater control practices is, therefore, dependent on their ability to remove these particles from the water, or possibly from intermediate accumulating locations (such as streets or other surfaces) and not through source reduction. The removal of these particles from stormwater is dependent on various characteristics of these particles, especially their size and settling rates. Some source area controls (most notably street cleaning) affect the particles before they are washed-off and transported by the runoff, while others remove the particles from the flowing water. This discussion, therefore summarizes the accumulation and washoff of these particulates and the particle size distribution of the suspended solids in stormwater runoff to better understand the effectiveness of source area control practices.

Table 4-1 shows that most of the organic compounds found in stormwater are associated with various human-related activities, especially automobile and pesticide use, or are associated with plastics (Verschueren 1983). Heavy metals found in stormwater also mostly originate from automobile use activities, including gasoline combustion, brake lining, fluids (e.g., brake fluid, transmission oil, anti-freeze, grease), undercoatings, and tire wear (Durum 1974, Koeppe 1977, Rubin 1976, Shaheen 1975, Solomon and Natusch 1977, and Wilbur and Hunter 1980). Auto repair, pavement wear, and deicing compound use also contribute heavy metals to stormwater (Field et al. 1973 and Shaheen 1975). Shaheen (1975) found that eroding area soils are the major source of the particulates in stormwater. The eroding area soil particles, and the particles associated with road surface wear, become contaminated with exhaust emissions and runoff containing the polluting compounds. Most of these compounds become tightly bound to these particles and are then transported through the urban area and drainage system, or removed from the stormwater, with the particulates. Stormwater concentrations of zinc, fluoranthene, 1,3-dichlorobenzene, and pyrene are unique in that substantial fractions of these compounds remain in the water and are less associated with the particulates.

All areas are affected by atmospheric deposition, while other sources of pollutants are specific to the activities conducted on the areas. As examples, the ground surfaces of unpaved equipment or material storage areas can become contaminated by spills and debris, while undeveloped land remaining relatively unspoiled by activities can still contribute runoff solids, organics, and nutrients, if eroded. Atmospheric deposition, deposition from activities on paved surfaces, and the erosion of material from upland unconnected areas are the major sources of pollutants in urban areas.

Table 4-1. Uses and sources for organic compounds found in stormwater (Verschuieren 1983).

COMPOUND	EXAMPLE USE/SOURCE
Phenol	gasoline, exhaust
N-Nitroso-di-n-propylamine	contaminant of herbicide Treflan
Hexachloroethane	plasticizer in cellulose esters, minor use in rubber and insecticide
Nitrobenzene	solvent, rubber, lubricants
2,4-Dimethylphenol	asphalt, fuel, plastics, pesticides
Hexachlorobutadiene	rubber and polymer solvent, transformer and hydraulic oil
4-Chloro-3-methylphenol	germicide; preservative for glues, gums, inks, textile, and leather
Pentachlorophenol	insecticide, algaecide, herbicide, and fungicide mfg., wood preservative
Fluoranthene	gasoline, motor and lubricating oil, wood preservative
Pyrene	gasoline, asphalt, wood preservative, motor oil
Di-n-octylphthalate	general use of plastics

Many studies have examined different sources of urban runoff pollutants. These references were reviewed as part of this study and the results are summarized in this section. These significant pollutants have been shown to have a potential for creating various receiving water impact problems, as described in Appendix D (???) of this report. Most of these potential problem pollutants typically have significant concentration increases in the urban feeder creeks and sediments, as compared to areas not affected by urban runoff.

The important sources of these pollutants are related to various uses and processes. Automobile related potential sources usually affect road dust and dirt quality more than other particulate components of the runoff system. The road dust and dirt quality is affected by vehicle fluid drips and spills (e.g., gasoline, oils) and vehicle exhaust, along with various vehicle wear, local soil erosion, and pavement wear products. Urban landscaping practices potentially affecting urban runoff include vegetation litter, fertilizer and pesticides. Miscellaneous sources of urban runoff pollutants include firework debris, wildlife and domestic pet wastes and possibly industrial and sanitary wastewaters. Wet and dry atmospheric contributions both affect runoff quality. Pesticide use in an urban area can contribute significant quantities of various toxic materials to urban runoff. Many manufacturing and industrial activities, including the combustion of fuels, also affect urban runoff quality.

Natural weathering and erosion products of rocks contribute the majority of the hardness and iron in urban runoff pollutants. Road dust and associated automobile use activities (gasoline exhaust products) historically contributed most of the lead in urban runoff. However, the decrease of lead in gasoline has resulted in current stormwater lead concentrations being about one tenth of the levels found in stormwater in the early 1970s (Bannerman et al. 1993). In certain situations, paint chipping can also be a major source of lead in urban areas. Road dust, contaminated by tire wear products and zinc plated metal erosion material, contributes most of the zinc to urban runoff. Urban landscaping activities can be a major source of cadmium (Phillips and Russo 1978). Electroplating and ore processing activities can also contribute chromium and cadmium.

Many pollutant sources are specific to a particular area and on-going activities. For example, iron oxides are associated with welding operations and strontium, used in the production of flares and fireworks, would probably be found on the streets in greater quantities around holidays, or at the scenes of traffic accidents. The relative contribution of each of these potential urban runoff sources, is, therefore, highly variable, depending upon specific site conditions and seasons.

Specific information is presented in the following subsections concerning the qualities of various rocks and soils, urban and rural dustfall, and precipitation. This information is presented to assist in the interpretation of the source area runoff samples collected as part of this project.

Chemical Quality of Rocks and Soils

The abundance of common elements in the lithosphere (the earth's crust) is shown in Table 4-2 (Lindsay 1979). Almost half of the lithosphere is oxygen and about 25% are silica. Approximately eight percent is aluminum and five percent is iron. Elements comprising between two percent and four percent of the lithosphere include calcium, sodium, potassium and magnesium. Because of the great abundance of these materials in the lithosphere, urban runoff transports only a relatively small portion of these elements to receiving waters, compared to natural processes. Iron and aluminum can both cause detrimental effects in receiving waters if in their dissolved forms. A reduction of the pH substantially increases the abundance of dissolved metals.

Table 4-2. Common elements in the Lithosphere (Lindsay 1979).

Abundance Rank	Element	Concentration in Lithosphere (mg/kg)
1	O	465,000
2	Si	276,000
3	Al	81,000
4	Fe	51,000
5	Ca	36,000
6	Na	28,000
7	K	26,000
8	Mg	21,000
9	P	1,200
10	C	950
11	Mn	900
12	F	625
13	S	600
14	Cl	500
15	Ba	430
16	Rb	280
17	Zr	220
18	Cr	200
19	Sr	150
20	V	150
21	Ni	100

Table 4-3, also from Lindsay (1979), shows the rankings for common elements in soils. These rankings are quite similar to the values shown previously for the lithosphere. Natural soils can contribute pollutants to urban runoff through local erosion. Again, iron and aluminum are very high on this list and receiving water concentrations of these metals are not expected to be significantly affected by urban activities alone.

Table 4-3. Common elements in soils (Lindsay 1979).

Abundance Rank	Element	Typical Minimum (mg/kg)	Typical Maximum (mg/kg)	Typical Average (mg/kg)
1	O	--	--	490,000
2	Si	230,000	350,000	320,000
3	Al	10,000	300,000	71,000
4	Fe	7,000	550,000	38,000
5	C	--	--	20,000
6	Ca	7,000	500,000	13,700
7	K	400	30,000	8,300
8	Na	750	7,500	6,300
9	Mg	600	6,000	5,000
10	Ti	1,000	10,000	4,000
11	N	200	4,000	1,400
12	S	30	10,000	700
13	Mn	20	3,000	600
14	P	200	5,000	600
15	Ba	100	3,000	430
16	Zr	60	2,000	300
17	F	10	4,000	200
18	Sr	50	1,000	200
19	Cl	20	900	100
20	Cr	1	1,000	100
21	V	20	500	100

The values shown on these tables are expected to vary substantially, depending upon the specific mineral types. Arsenic is mainly concentrated in iron and manganese oxides, shales, clays, sedimentary rocks and phosphorites. Mercury is concentrated mostly in sulfide ores, shales and clays. Lead is fairly uniformly distributed, but can be concentrated in clayey sediments and sulfide deposits. Cadmium can also be concentrated in shales, clays and phosphorites (Durum 1974).

Street Dust and Dirt Pollutant Sources

Characteristics

Most of the street surface dust and dirt materials (by weight) are local soil erosion products, while some materials are contributed by motor vehicle emissions and wear (Shaheen 1975). Minor contributions are made by erosion of street surfaces in good condition. The specific makeup of street surface contaminants is a function of many conditions and varies widely (Pitt 1979).

Automobile tire wear is a major source of zinc in urban runoff and is mostly deposited on street surfaces and nearby adjacent areas. About half of the airborne particulates

lost due to tire wear settle out on the street and the majority of the remaining particulates settle within about six meters of the roadway. Exhaust particulates, fluid losses, drips, spills and mechanical wear products can all contribute lead to street dirt. Many heavy metals are important pollutants associated with automobile activity. Most of these automobile pollutants affect parking lots and street surfaces. However, some of the automobile related materials also affect areas adjacent to the streets. This occurs through the wind transport mechanism after being resuspended from the road surface by traffic-induced turbulence.

Automobile exhaust particulates contribute many important heavy metals to street surface particulates and to urban runoff and receiving waters. The most notable of these heavy metals has been lead. However, since the late 1980s, the concentrations of lead in stormwater has decreased substantially (by about ten times) compared to early 1970 observations. This decrease, of course, is associated with significantly decreased consumption of leaded gasoline.

Solomon and Natusch (1977) studied automobile exhaust particulates in conjunction with a comprehensive study of lead in the Champaign-Urbana, IL area. They found that the exhaust particulates existed in two distinct morphological forms. The smallest particulates were almost perfectly spherical, having diameters in the range of 0.1 to 0.5 μm . These small particles consisted almost entirely of PbBrCl (lead, bromine, chlorine) at the time of emission. Because the particles are small, they are expected to remain airborne for considerable distances and can be captured in the lungs when inhaled. The researchers concluded that the small particles are formed by condensation of PbBrCl vapor onto small nucleating centers, which are probably introduced into the engine with the filtered engine air.

Solomon and Natusch (1977) found that the second major form of automobile exhaust particulates were rather large, being roughly 10 to 20 μm in diameter. These particles typically had irregular shapes and somewhat smooth surfaces. The elemental compositions of these irregular particles were found to be quite variable, being predominantly iron, calcium, lead, chlorine and bromine. They found that individual particles did contain aluminum, zinc, sulfur, phosphorus and some carbon, chromium, potassium, sodium, nickel and thallium. Many of these elements (bromine, carbon, chlorine, chromium, potassium, sodium, nickel, phosphorus, lead, sulfur, and thallium) are most likely condensed, or adsorbed, onto the surfaces of these larger particles during passage through the exhaust system. They believed that these large particles originate in the engine or exhaust system because of their very high iron content. They found that 50 to 70 percent of the emitted lead was associated with these large particles, which would be deposited within a few meters of the emission point onto the roadway, because of their aerodynamic properties.

Solomon and Natusch (1977) also examined urban particulates near roadways and homes in urban areas. They found that lead concentrations in soils were higher near roads and houses. This indicated the capability of road dust and peeling house paint to

contaminate nearby soils. The lead content of the soils ranged from 130 to about 1,200 mg/kg. Koeppe (1977), during another element of the Champaign-Urbana lead study, found that lead was tightly bound to various soil components. However, the lead did not remain in one location, but it was transported both downward in the soil profile and to adjacent areas through both natural and man-assisted processes.

Street Dirt Accumulation

The washoff of street dirt and the effectiveness of street cleaning as a stormwater control practice are highly dependent on the available street dirt loading. Street dirt loadings are the result of deposition and removal rates, plus “permanent storage.” The permanent storage component is a function of street texture and condition and is the quantity of street dust and dirt that cannot be removed naturally or by street cleaning equipment. It is literally trapped in the texture, or cracks, of the street. The street dirt loading at any time is this initial permanent loading plus the accumulation amount corresponding to the exposure period, minus the re-suspended material removal by wind and traffic-induced turbulence. Removal of street dirt can occur naturally by winds and rain, or by human activity (e.g., by the turbulence of traffic or by street cleaning equipment). Very little removal occurs by any process when the street dirt loadings are small, but wind removal may be very large with larger loadings, especially for smooth streets (Pitt 1979).

Figure 4-1 shows very different street dirt loadings for two San Jose, CA residential study areas (Pitt 1979). The accumulation and deposition rates (and therefore the amounts lost to air) are quite similar, but the initial loading values (the permanent storage values) are very different. The loading differences were almost solely caused by the different street textures.

Table 4-4 summarizes many accumulation rate measurements obtained from throughout North America. In the earliest studies (APWA 1969; Sartor and Boyd 1972; and Shaheen 1975), the initial street dirt loading values after a major rain or street cleaning were assumed to be zero. Calculated accumulation rates for rough streets were, therefore, very large. Later tests measured the initial loading values close to the end of major rains and street cleaning and found that they could be very high, depending on the street texture. When these starting loadings were considered, the calculated accumulation rates were, therefore, much lower. The early, uncorrected, Sartor and Boyd accumulation rates that ignored the initial loading values were almost ten times the correct values shown on this table. Unfortunately, most urban stormwater models used these very high early accumulation rates as default values.

The most important factors affecting the initial loading and maximum loading values shown on Table 4-4 were found to be street texture and street condition. When data from many locations are studied, it is apparent that smooth streets have substantially less loadings at any accumulation period compared to rough streets for the same land use. Very long accumulation periods relative to the rain frequency resultant in high street dirt loadings. During these conditions, the wind losses of street dirt (as fugitive

dust) may approximate the deposition rate, resulting in relatively constant street dirt loadings. At Bellevue, WA, typical interevent rain periods average about three days. Relatively constant street dirt loadings were observed in Bellevue because the frequent rains kept the loadings low and very close to the initial storage value, with little observed increase in dirt accumulation over time (Pitt 1985). In Castro Valley, CA, the rain interevent periods were much longer (ranging from about 20 to 100 days) and steady loadings were only observed after about 30 days when the loadings became very high and fugitive dust losses caused by the winds and traffic turbulence moderated the loadings (Pitt and Shawley 1982).

An example of the type of research conducted to obtain the values shown in Table 4-4 was conducted by Pitt and McLean (1986) in Toronto. They measured street dirt accumulation rates and the effects of street cleaning as part of a comprehensive stormwater research project. An industrial street with heavy traffic and a residential street with light traffic were monitored about twice a week for three months. At the beginning of this period, intensive street cleaning (one pass per day for each of three consecutive days) was conducted to obtain reasonably clean streets. Street dirt loadings were then monitored every few days to measure the accumulation rates of street dirt. Street dirt sampling procedures developed by Pitt (1979) were applied. Powerful industrial vacuums (two units, each having two HP, combined with a "Y" connector, and using a six inch wide solid aluminum head) were used to clean many separate subsample strips across the roads which were then combined for physical and chemical analyses.

In Toronto, the street dirt particulate loadings were quite high before the initial intensive street cleaning period and were reduced to their lowest observed levels immediately after the last street cleaning. After street cleaning, the loadings on the industrial street increased much faster than for the residential street. Right after intensive cleaning, the street dirt particle sizes were also similar for the two land uses. However, the loadings of larger particles on the industrial street increased at a much faster rate than on the residential street, indicating more erosion or tracking materials being deposited onto the industrial street. The residential street dirt measurements did not indicate that any material was lost to the atmosphere as fugitive dust, probably because of the low street dirt accumulation rate and the short periods of time between rains. The street dirt loadings never had the opportunity to reach the high loading values needed before they could be blown from the streets by winds or by traffic-induced turbulence. The industrial street, in contrast, had a much greater street dirt accumulation rate and reached the critical loading values needed for fugitive losses in the relatively short periods between the rains.

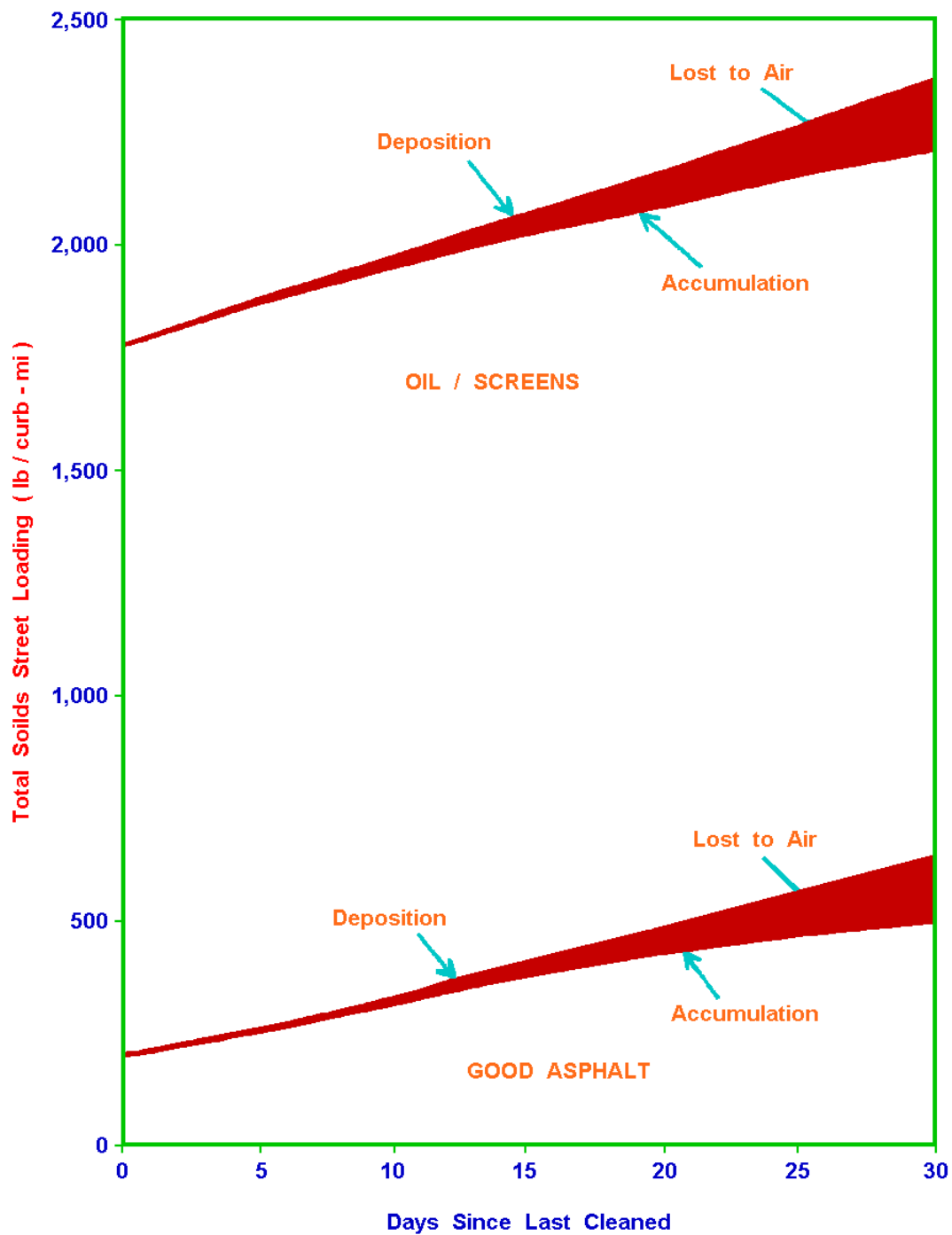


Figure 4-1. Deposition and accumulation of street dirt (Pitt 1979).

Table 4-4. Street dirt loadings and deposition rates.

	Initial Loading Value (grams/curb-meter)	Daily Deposition Rate (grams/curb-meter-day)	Maximum Observed Loading (grams/curb-meter)	Days to Observed Maximum Loading	Reference
Smooth and Intermediate Textured Streets					
Reno/Sparks, NV – good condition	80	1	85	5	Pitt and Sutherland 1982
Reno/Sparks, NV – good with smooth gutters (windy)	250	7	400	30	Pitt and Sutherland 1982
San Jose, CA – good condition	35	4	>140	>50	Pitt 1979
U.S. nationwide – residential streets, good condition	110	6	140	5	Sartor and Boyd 1972 (corrected)
U.S. nationwide – commercial street, good condition	85	4	140	5	Sartor and Boyd 1972 (corrected)
Reno/Sparks, NV – moderate to poor condition	200	2	200	5	Pitt and Sutherland 1982
Reno/Sparks, NV – new residential area (construction)	710	17	910	15	Pitt and Sutherland 1982
Reno/Sparks, NV – poor condition, with lipped gutters	370	15	630	35	Pitt and Sutherland 1982
San Jose, CA – fair to poor condition	80	4	230	70	Pitt 1979
Castro Valley, CA – moderate condition	85	10	290	70	Pitt and Shawley 1982
Ottawa, Ontario – moderate condition	40	20	Na	Na	Pitt 1983
Toronto, Ontario – moderate condition, residential	40	32	100	>10	Pit and McLean 1986
Toronto, Ontario – moderate condition, industrial	60	40	351	>10	Pit and McLean 1986
Bellevue, WA – dry period, moderate condition	140	6	>230	20	Pitt 1984
Bellevue, WA – heavy traffic	60	1	110	30	Pitt 1984
Bellevue, WA – other residential sites	70	3	140	30	Pitt 1984
Average:	150	9	>270	>25	
Range:	35 – 710	1 – 40	85 – 910	5 – 70	
Rough and Very Rough Textured Streets					
San Jose, CA – oil and screens overlay	510	6	>710	>50	Pitt 1979
Ottawa, Ontario – very rough	310	20	Na	Na	Pitt 1983
Reno/Sparks, NV	630	10	860	35	Pitt and Sutherland 1982
Reno/Sparks, NV – windy	540	34	>1,400	>40	Pitt and Sutherland 1982
San Jose, CA – poor condition	220	6	430	30	Pitt 1979
Ottawa, Ontario – rough	200	20	Na	Na	Pitt 1983
U.S. nationwide – industrial streets (poor condition)	190	10	370	10	Sartor and Boyd 1972 (corrected)
Average:	370	15	>750	>30	
Range:	190 - 630	6 - 34	370 - >1,400	10 - >50	

Washoff of Street Dirt

The Yalin equation relates the sediment carrying capacity to runoff flow rate (Yalin 1963). Yalin stated that sediment motion begins when the lift force of flow exceeds a critical lift force. Once a particle is lifted, the drag force of the flow moves it downstream until the weight of the particle forces it back down. The Yalin equation is used to predict particle transport, for specific particle sizes, on a weight per unit flow width basis. It is used for fully turbulent channel flow conditions, typical of shallow overland flow in urban areas. The receding limb (tail) of a hydrograph may have laminar flow conditions, and the suspended sediment carried in the previously turbulent flows would settle out. The predicted constant Yalin sediment load would therefore only occur during periods of rain, and, the sediment load would decrease, due to sedimentation, after the rain stops.

The critical particle bedload tractive force, the tractive force at which the particle begins to move, can be obtained from the Shields' diagram. However, Shen (1981) warned that the Shields' diagram alone cannot be used to predict "self-cleaning" velocities, because it gives only a lower limit below which deposition will occur. It defines the boundary between bed movement and stationary bed conditions. The Shields' diagram does not consider the particulate supply rate in relationship to the particulate transport rate. Reduced particulate transport occurs if the sediment supply rate is less than the transport rate. The Yalin equation by itself is, therefore, not sensitive to particulate supply; it only predicts the carrying capacity of flowing waters.

Besides the particulate supply rate, the Yalin equation is also very sensitive to local flow parameters (specifically gutter flow depth). Therefore, a hydraulic model that can accurately predict sheetflow across impervious surfaces and gutter flow is needed. Sutherland and McCuen (1978) statistically analyzed a modified form of the Yalin equation, in conjunction with a hydraulic model for different gutter flow conditions. Except for the largest particle sizes, the effect of rain intensity on particle washoff was found to be negligible.

The Yalin equation is based on classical sediment transport equations and requires some assumptions concerning the micro-scale aspects of gutter flows and street dirt distributions. The Yalin equation, as typically used in urban stormwater evaluations, assumes that all particles lie within the gutter and no significant washoff occurs by sheetflows traveling across the street towards the gutter. The early measurements of across-the-street dirt distributions made by Sartor and Boyd (1972) indicated that about 90 percent of the street dirt was within about 30 cm of the curb face (typically within the gutter area). These measurements, however, were made in areas of no parking (near fire hydrants because of the need for water for the sampling procedures that were used) and the traffic turbulence was capable of blowing most of the street dirt against the curb barrier (or over the curb onto adjacent sidewalks or landscaped areas) (Shaheen 1975).

In later tests, Pitt (1979) and Pitt and Sutherland (1982) examined street dirt distributions across the street in many additional situations. They found distributions similar to Sartor and Boyd's observations only on smooth streets, with moderate to

heavy traffic, and with no on-street parking. In many cases, most of the street dirt was actually in the driving lanes, trapped by the texture of rough streets. If extensive on-street parking was common, much of the street dirt was found on the outside edge of the parking lanes, where much of the resuspended (in air) street dirt blew against the parked cars and settled to the pavement.

Another process that may result in washoff less than predicted by Yalin is bed armoring (Sutherland et al. 1982). As the smaller particulates are removed, the surface is covered by predominantly larger particulates which are not effectively washed-off by rain. Eventually, these larger particulates hinder the washoff of the trapped, underlying, smaller particulates. Debris on the street, especially leaves, can also effectively armor the particulates, reducing the washoff of particulates to very low levels (Singer and Blackard 1978).

Observations of particulate washoff during controlled tests using actual streets and natural street dirt and debris are affected by street dirt distributions and armoring. The earliest controlled street dirt washoff experiments were conducted by Sartor and Boyd (1972) during the summer of 1970 in Bakersfield, CA. Their data were used in many stormwater models (including SWMM, Huber and Heaney 1981; STORM, COE 1975; and HSPF, Donigian and Crawford 1976) to estimate the percentage of the available particulates on the streets that would wash off during rains of different magnitudes. Sartor and Boyd used a rain simulator having many nozzles and a drop height of 1.5 to two meters in street test areas of about five by ten meters. Tests were conducted on concrete, new asphalt, and old asphalt, using simulated rain intensities of about five and 20 mm/hr. They collected and analyzed runoff samples every 15 minutes for about two hours for each test. Sartor and Boyd fitted their data to an exponential curve, assuming that the rate of particle removal of a given size is proportional to the street dirt loading and the constant rain intensity:

$$dN/dt = krN$$

where: dN/dt = the change in street dirt loading per unit time
 k = proportionality constant (1/hr)
 r = rain intensity (in/hr)
 N = street dirt loading (lb/curb-mile)

This equation, upon integration, becomes:

$$N = N_0 e^{-krt}$$

where: N = residual street dirt load (after the rain)
 N_0 = initial street dirt load
 t = rain duration (hr)

Street dirt washoff is, therefore, equal to N_0 minus N . The variable combination rt , or

rain intensity (in/hr) times rain duration (t), is equal to total rain depth (R), in inches. This equation then further reduces to:

$$N = N_0 e^{-kR}$$

Therefore, this equation is only sensitive to the total depth of the rain that has fallen since the beginning of the rain, and not rain intensity. Because of decreasing particulate supplies, the exponential washoff curve also predicts decreasing concentrations of particulates with time since the start of a constant rain (Alley 1980 and 1981).

The proportionality constant, k, was found by Sartor and Boyd to be slightly dependent on street texture and condition, but was independent of rain intensity and particle size. The value of this constant is usually taken as 0.18/mm, assuming that 90 percent of the particulates will be washed from a paved surface in one hour during a 13 mm/hr rain. However, Alley (1981) fitted this model to watershed outfall runoff data and found that the constant varied for different storms and pollutants for a single study area. Novotny (as part of Bannerman et al. 1983) also examined “before” and “after” rain event street particulate loading data from the Milwaukee Nationwide Urban Runoff Program (NURP) project and found almost a three-fold difference between the constant value of k for fine (<45 µm) and medium sized particles (100 to 250 µm). The calculated values were 0.026/mm for the fine particles and 0.01/mm for the medium sized particles, both much less than the “accepted” value of 0.18/mm. Jewell et al. (1980) also found large variations in outfall “fitted” constant values for different rains compared to the typical default value. Either the assumption of the high removal of particulates during the 13 mm/hr storm was incorrect or/and the equation cannot be fitted to outfall data (most likely, as this would require that all the particulates are originating from homogeneous paved surfaces during all storm conditions).

This washoff equation has been used in many stormwater models, along with an expression for an availability factor. An availability factor is needed, because N_0 is only the portion of the total street load available for washoff. This availability factor (the fraction of the total street dirt loading available for washoff) is generally used as 1.0 for all rain intensities greater than about 18 mm/hr and reduces to about 0.10 for rains of one mm/hr.

The Bellevue, WA urban runoff project (Pitt 1985) included about 50 pairs of street dirt loading observations close to the beginnings and ends of rains. These “before” and “after” loading values were compared to determine significant differences in loadings that may have been caused by the rains. The observations were affected by rains falling directly on the streets, along with flows and particulates originating from non-street areas. The net loading differences were, therefore, affected by street dirt washoff (by direct rains on the street surfaces and by gutter flows augmented by “upstream” area runoff) and by erosion products that originated from non-street areas that may have settled out in the gutters. When all the data were considered together, the net

loading difference was about 10 to 13 g/curb-m removed. This amounted to a street dirt load reduction of about 15 percent, which was much less than predicted using either of the two previously described washoff models. Very large reductions in street dirt loadings during rains were observed in Bellevue for the smallest particles, but the largest particles actually increased in loadings (due to deposited erosion materials originating from off-street areas). The particles were not source limited, but armor shielding may have been important. Most of the particulates in the runoff were in the fine particle sizes ($<63\ \mu\text{m}$). Very few particles greater than $1000\ \mu\text{m}$ were found in the washoff water. Care must be taken to not confuse street dirt particle size distributions with stormwater runoff particle size distributions. The stormwater particle size distributions are much more biased towards the smaller sizes, as described later.

Suspended solids washoff predictions for Bellevue conditions were made using the Sutherland and McCuen modification of the Yalin equation and the Sartor and Boyd equation. Three particle size groups (<63 , 250-500, and 2000-6350 μm), and three rains, having depths of 5, 10, and 20 mm and 3-hr durations, were considered. The gutter lengths for the Bellevue test areas averaged about 80 m, with gutter slopes of about 4.5%. Typical total initial street dirt loadings for the three particle sizes were: 9 g/curb-m for $<63\ \mu\text{m}$, 18 g/curb-m for 250-500 μm , and 9 g/curb-m for 2000-6350 μm . The actual Bellevue net loading removals during the storms were about 45% for the smallest particle size group, 17% for the middle particle size group, and minus six percent (six percent loading increase) for the largest particle size group. The predicted removals were 90 to 100% using the Sutherland and McCuen method, 61 to 98% using the Sartor and Boyd equation, and 8 to 37% using the availability factor with the Sartor and Boyd equation. The ranges given reflect the different rain volumes and intensities only. There were no large predicted differences in removal percentages as a function of particle size. The availability factor with the Sartor and Boyd equation resulted in the closest predicted values, but the great differences in washoff as a function of particle size was not predicted.

The Bellevue street dirt washoff observations included effects of additional runoff water and particulates originating from non-street areas. The additional flows should have produced more gutter particulate washoff, but upland erosion materials may also have settled in the gutters (as noted for the large particles). However, across-the-street particulate loading measurements indicated that much of the street dirt was in the street lanes, not in the gutters, before and after rains. This particulate distribution reduces the importance of these extra flows and particulates from upland areas. The increased loadings of the largest particles after rains were obviously caused by upland erosion, but the magnitude of the settled amounts was quite small compared to the total street dirt loadings.

In order to clarify street dirt washoff, Pitt (1987) conducted numerous controlled washoff tests on city streets in Toronto. These tests were arranged as an overlapping series of 2^3 factorial tests, and were analyzed using standard factorial test procedures described by Box et al. (1978). The experimental factors examined included: rain intensity, street

texture, and street dirt loading. The differences between available and total street dirt loads were also related to the experimental factors. The samples were analyzed for total solids (total residue), dissolved solids (filterable residue: $<0.45\ \mu\text{m}$), and SS (particulate residue: $>0.45\ \mu\text{m}$). Runoff samples were also filtered through $0.45\ \mu\text{m}$ filters and the filters were microscopically analyzed (using low power polarized light microscopes to differentiate between inorganic and organic debris) to determine particulate size distributions from about 1 to $500\ \mu\text{m}$. The runoff flow quantities were also carefully monitored to determine the magnitude of initial and total rain water losses on impervious surfaces.

The total solids concentrations varied from about 25 to $3000\ \text{mg/l}$, with an obvious decrease in concentrations with increasing rain depths during these constant rain intensity tests. No concentrations greater than $500\ \text{mg/l}$ occurred after about two mm of rain. All concentrations after about 10 mm of rain were less than $100\ \text{mg/l}$. Total solids concentrations were independent of the test conditions. A wide range in runoff concentrations was also observed for SS, with concentrations ranging from about 1 to $3000\ \text{mg/l}$. Again, a decreasing trend of concentrations was seen with increasing rain depths, but the data scatter was larger because of the experimental factors. The dissolved solids ($<0.45\ \mu\text{m}$) concentrations ranged from about 20 to $900\ \text{mg/l}$, comprising a surprisingly large percentage of the total solids loadings. For small rain depths, dissolved solids comprised up to 90 percent of the total solids. After 10 mm of rain depth, the filterable residue concentrations were all less than about $50\ \text{mg/l}$.

Manual particle size analyses were also conducted on the suspended solids washoff samples, using a microscope with a calibrated recticle. Figures 4-2 and 4-3 are examples of particle size distributions for two tests. These plots show the percentage of the particles that were less than various sizes, by measured particle volume (assumed to be similar to weight). The plots also indicate median particle sizes of about 10 to $50\ \mu\text{m}$, depending on when the sample was obtained during the washoff tests. All of the distributions showed surprisingly similar trends of particle sizes with elapsed rain depth. The median size for the sample obtained at about one mm of rain was much greater than for the samples taken after more rain. The median particle sizes of material remaining on the streets after the washoff tests were also much larger than for most of the runoff samples, but were quite close to the initial samples' median particle sizes. The washoff water at the very beginning of the test rains, therefore, contained many more larger particles than during later portions of the rains. Also, a substantial amount of larger particles remained on the streets after the test rains. Most street runoff waters during test rains in the 5 to 15 mm depth category had median suspended solids particle sizes of about 10 to $50\ \mu\text{m}$. However, dissolved solids (less than $0.45\ \mu\text{m}$) made up most of the total solids washoff for elapsed rain depths greater than about five mm.

These particle size distributions indicate that the smaller particles were much more important than indicated during previous tests. As an example, the Sartor and Boyd (1972) washoff tests (rain intensities of $50\ \text{mm/h}$ for two hour durations) found median

particle sizes of about 150 μm which were typically three to five times larger than were found during these tests. They also did not find any significant particle size distribution differences for different rain depths (or rain duration), in contrast to the Toronto tests, which were conducted at more likely rain intensities (3 to 12 mm/hr for two hours).

The particulate washoff values obtained during these Toronto tests were expressed in units of grams per square meter and grams per curb-meter, concentrations (mg/l), and the percent of the total initial loading washed off during the test. Plots of accumulative washoff are shown on Figures 4-4 through 4-11. These plots show the asymptotic washoff values observed in the tests, along with the measured total street dirt loadings. The maximum asymptotic values are the “available” street dirt loadings (N_o). The measured total loadings are seen to be several times larger than these “available” loading values. As an example, the asymptotic available total solids value for the HDS (high intensity rain, dirty street, smooth street) test (Figure 4-10) was about 3 g/m² while the total load on the street for this test was about 14 g/m², or about five times the available load. The differences between available and total loadings for the other tests were even greater, with the total loads typically about ten times greater than the available loads. The total loading and available loading values for dissolved solids were quite close, indicating almost complete washoff of the very small particles. However, the differences between the two loading values for SS were much greater. Shielding, therefore, may not have been very important during these tests, as almost all of the smallest particles were removed, even in the presence of heavy loadings of large particles.

The actual data are shown on these figures, along with the fitted Sartor and Boyd exponential washoff equations. In many cases, the fitted washoff equations greatly over-predicted suspended solids washoff during the very small rains (usually less than one to three mm in depth). In all cases, the fitted washoff equations described suspended solids washoff very well for rains greater than about 10 mm in depth.

Table 4-5 presents the equation parameters for each of the eight washoff tests for suspended solids. Pitt (1987) concluded that particulate washoff should be divided into two main categories, one for high intensity rains with dirty streets, possibly divided into categories by street texture, and the other for all other conditions. Factorial tests also found that the availability factor (the ratio of the available loading, N_o , to the total loading) varied depending on the rain intensity and the street roughness, as indicated below:

- Low rain intensity and rough streets: 0.045
- High rain intensity and rough streets, or low rain intensity and smooth streets: 0.075
- High rain intensity and smooth streets: 0.20

Obviously, washoff was more efficient for the higher rain energy and smoother pavement tests. The worst case was for a low rain intensity and rough street, where

only about 4.5% of the street dirt would be washed from the pavement. In contrast, the high rain intensities on the smooth streets were more than four times more efficient in removing the street dirt.

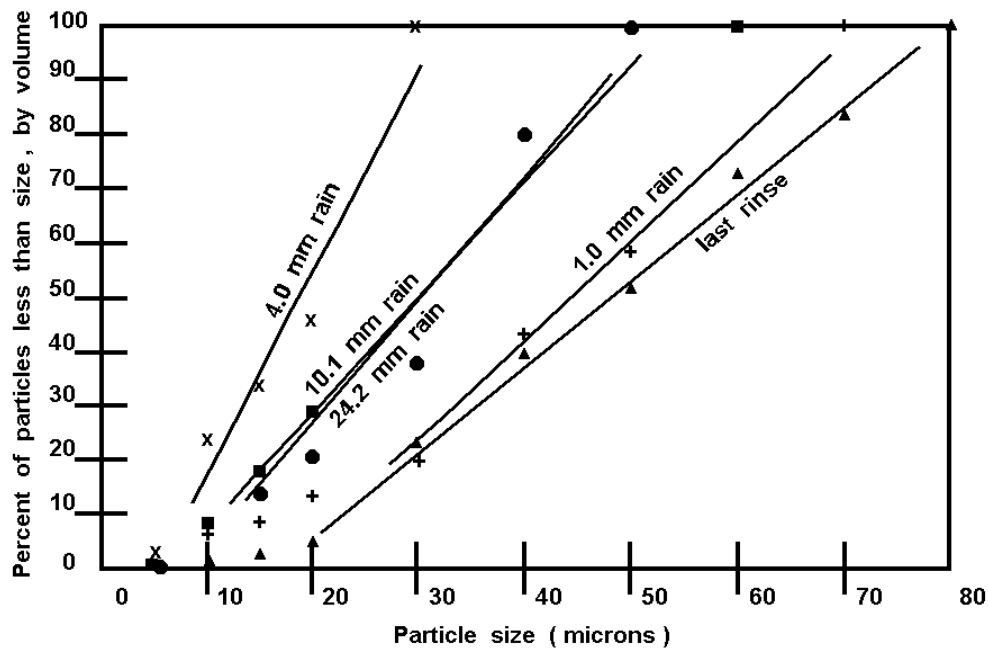


Figure 4-2. Particle size distribution of HDS test (high rain intensity, dirty, and smooth street) (Pitt 1987).

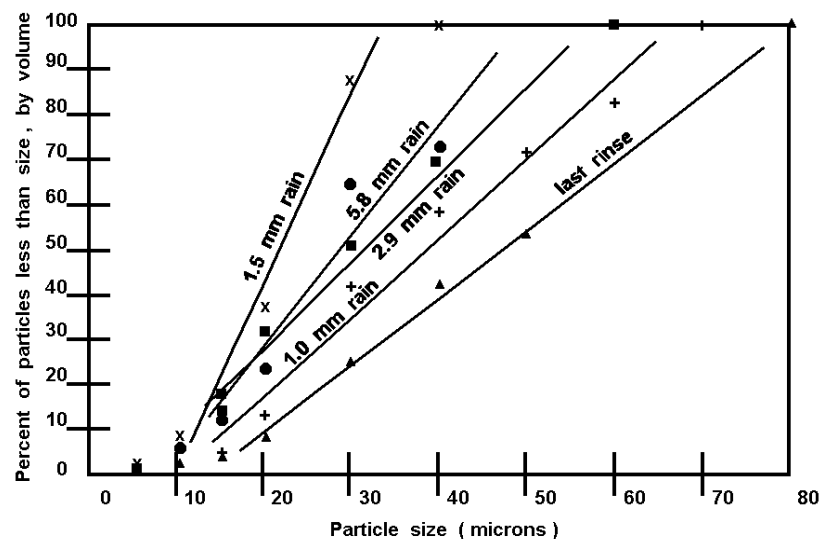


Figure 4-3. Particle size distribution for LCR test (light rain intensity, clean, and rough street) (Pitt 1987).

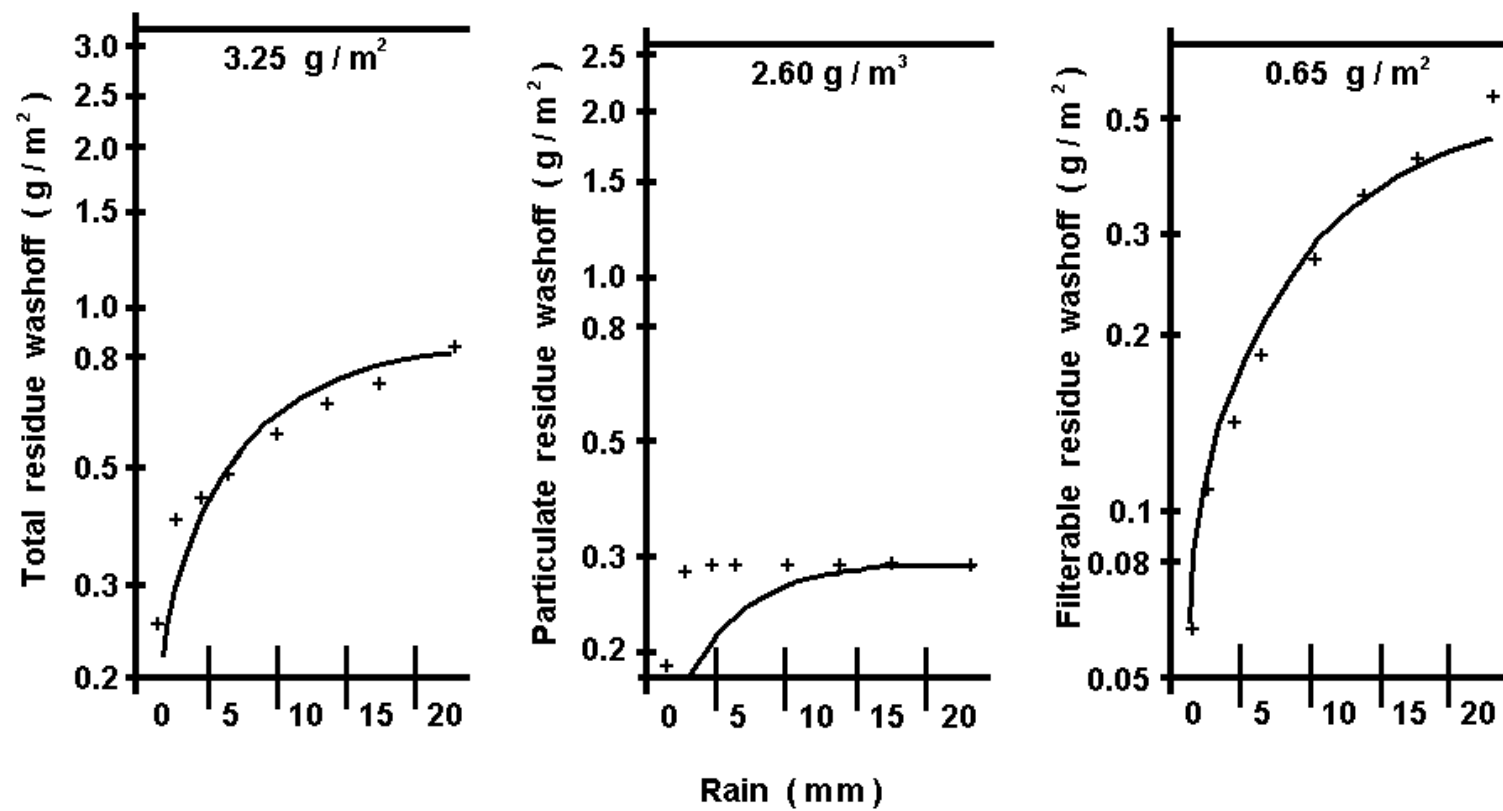


Figure 4-4. Washoff plots for HCR test (high rain intensity, clean, and rough street) (Pitt 1987).

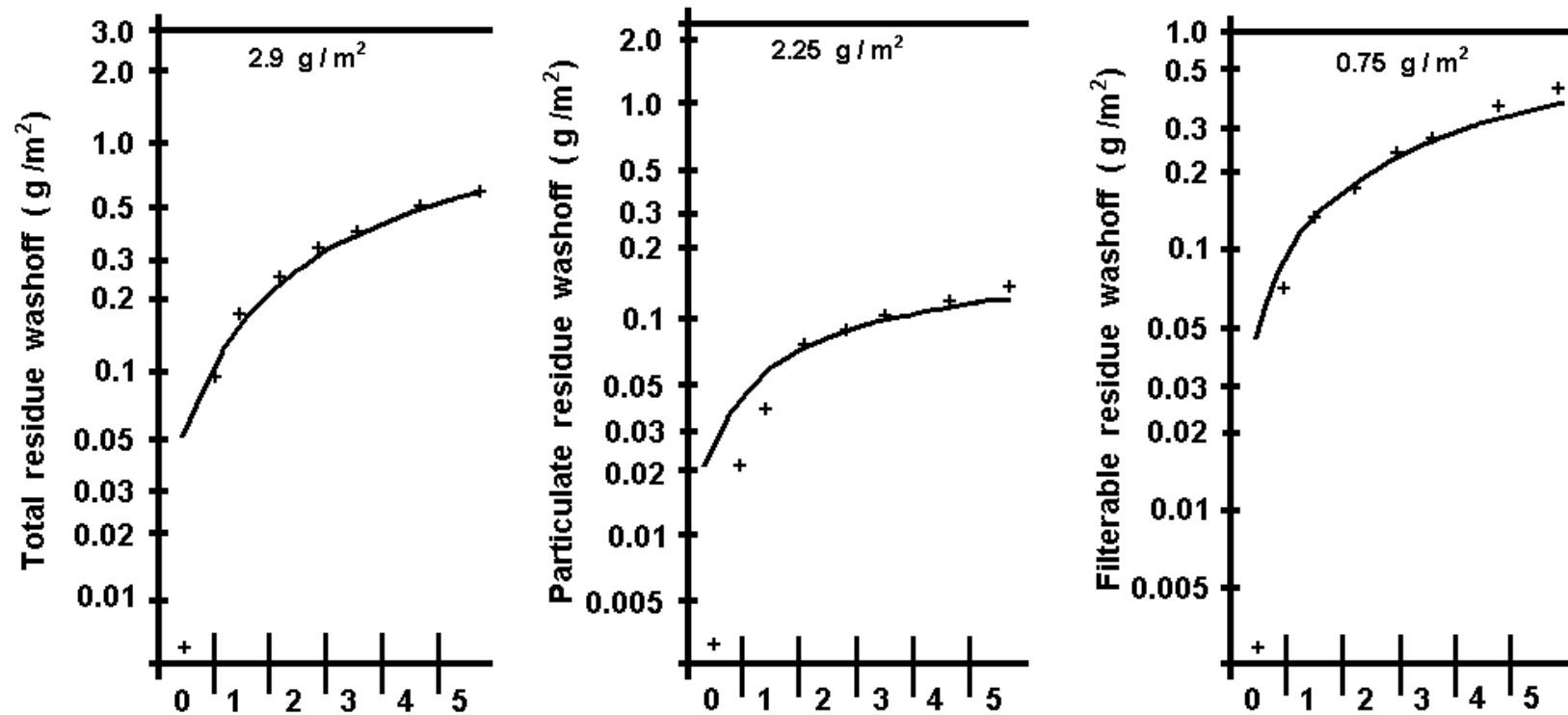


Figure 4-5. Washoff plots for LCR test (light rain intensity, clean, and rough street) (Pitt 1987).

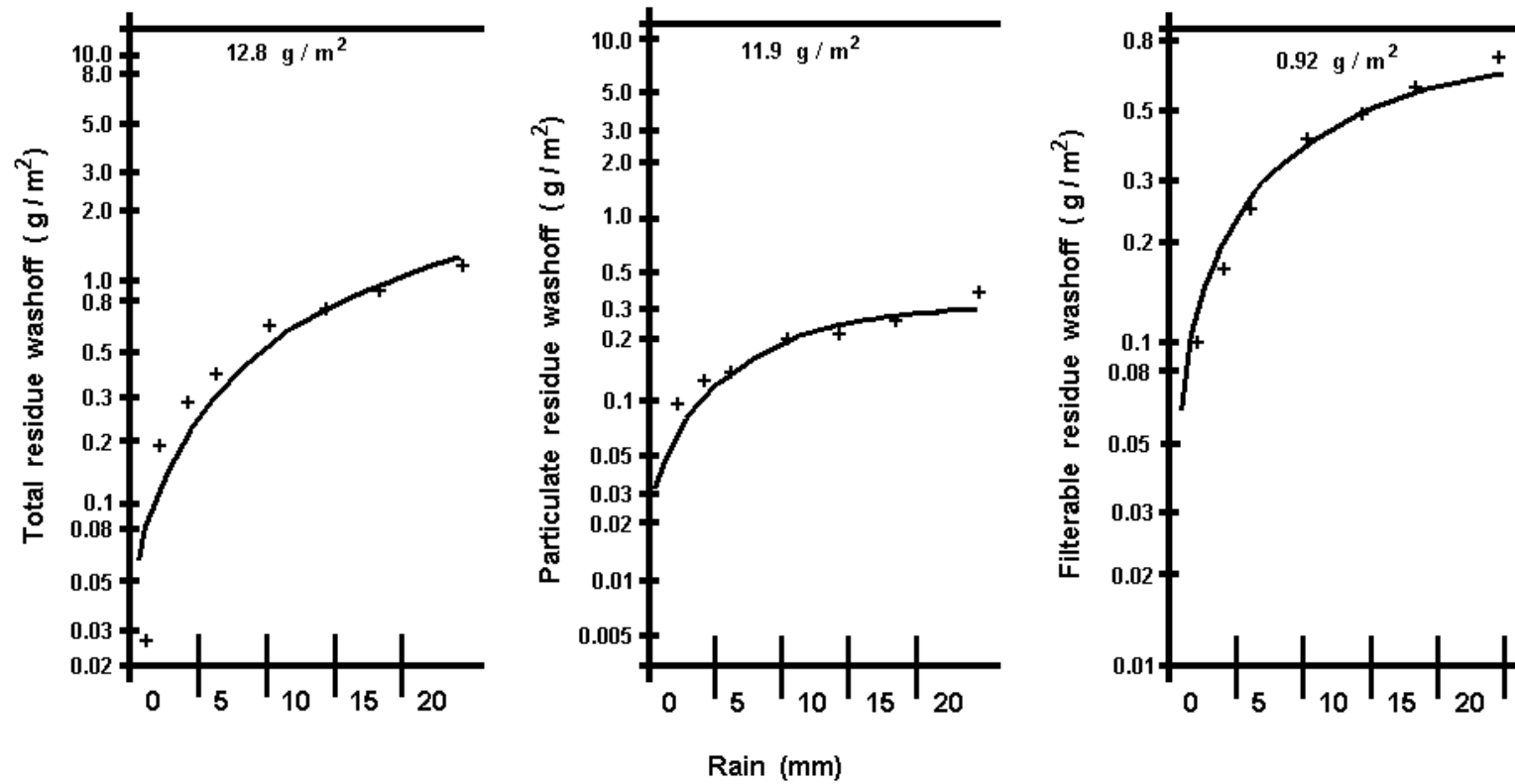


Figure 4-6. Washoff plots for HDR test (high rain intensity, dirty, and rough street) (Pitt 1987).

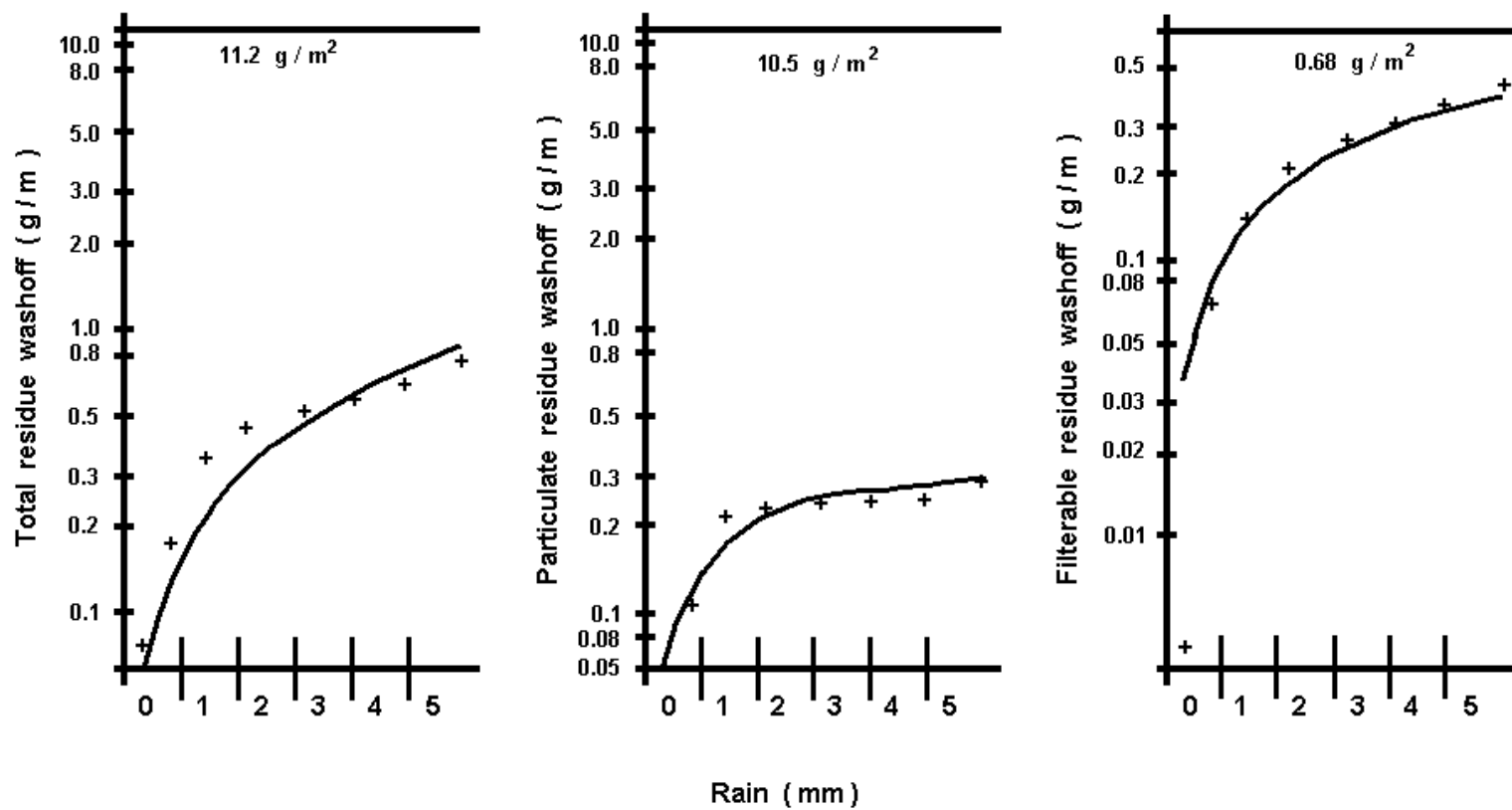


Figure 4-7. Washoff plots for LDR test (light rain intensity, dirty, and rough street) (Pitt 1987).

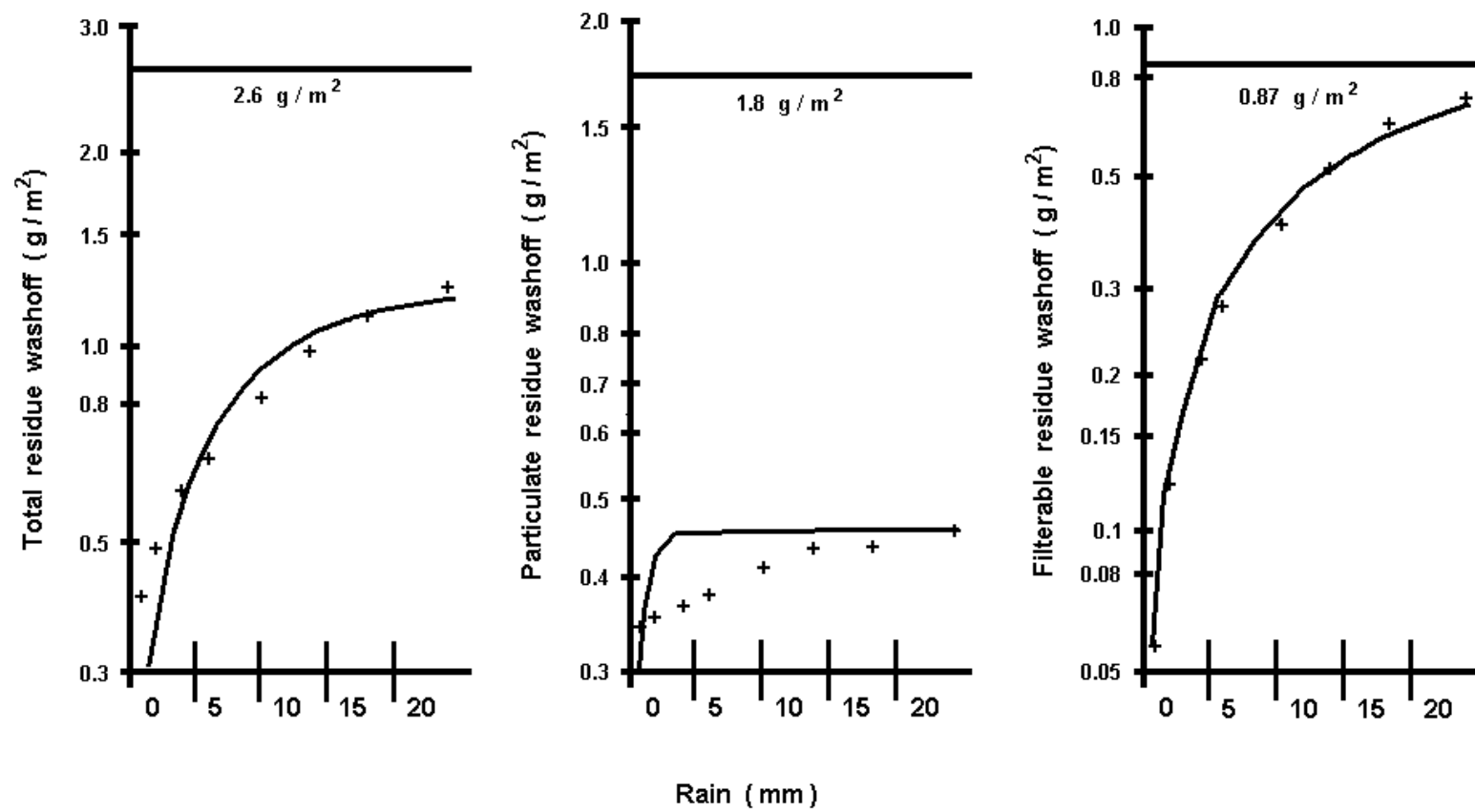


Figure 4-8. Washoff plots for HCS test (high rain intensity, clean, and smooth street) (Pitt 1987).

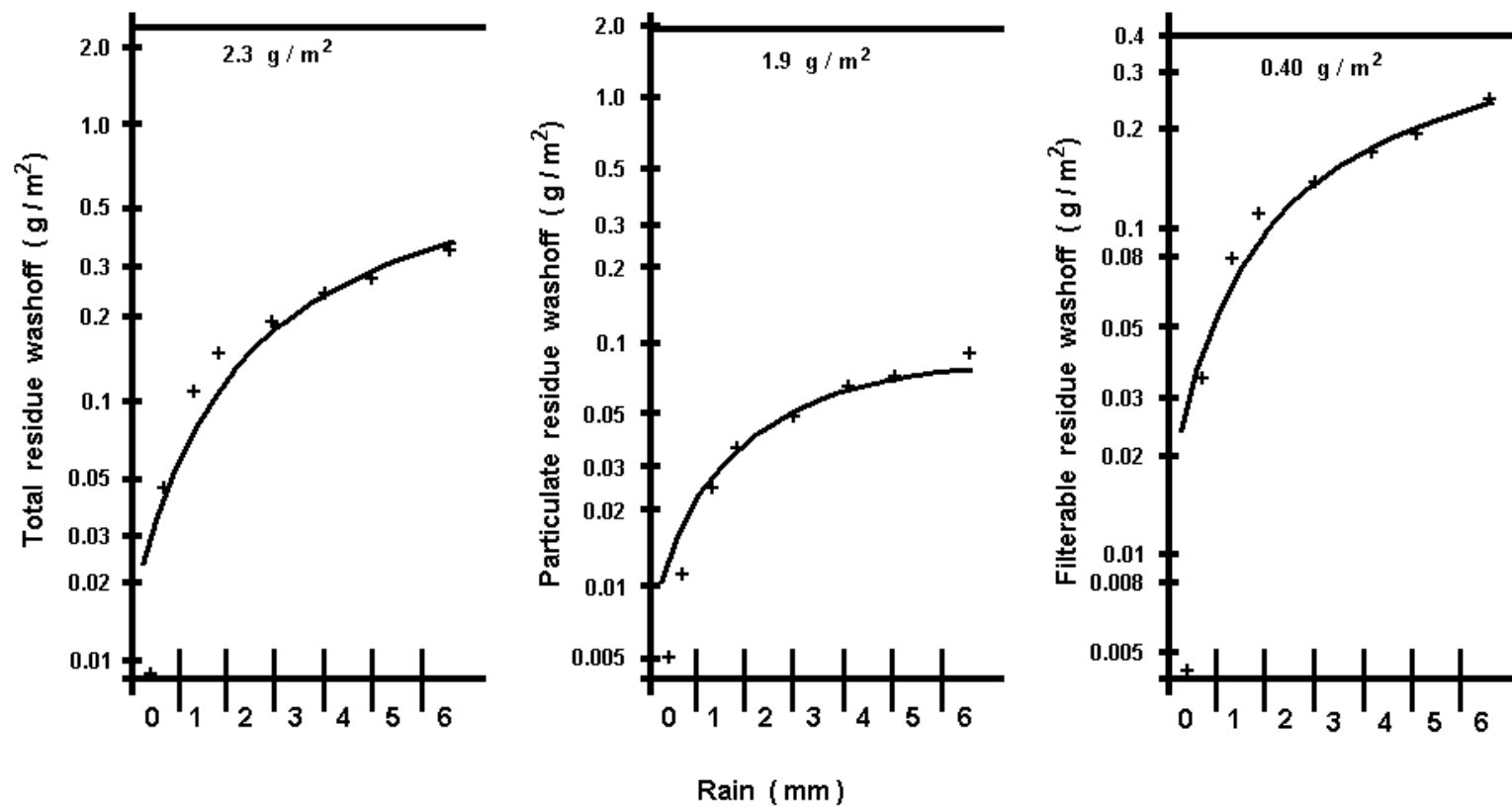


Figure 4-9. Washoff plots for LCS test (light rain intensity, clean, and smooth street) (Pitt 1987).

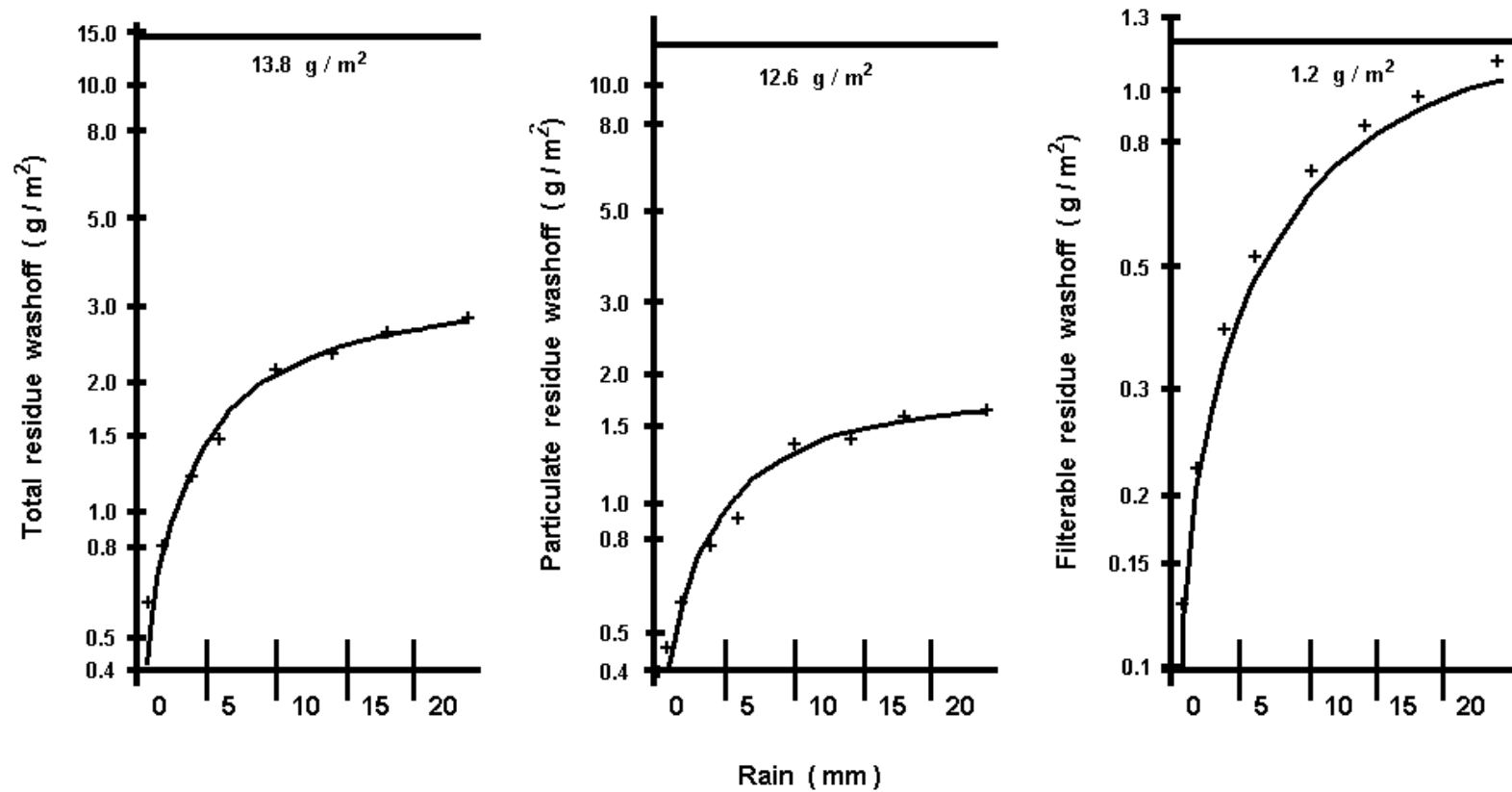


Figure 4-10. Washoff plots for HDS test (high rain intensity, dirty, and smooth street) (Pitt 1987).

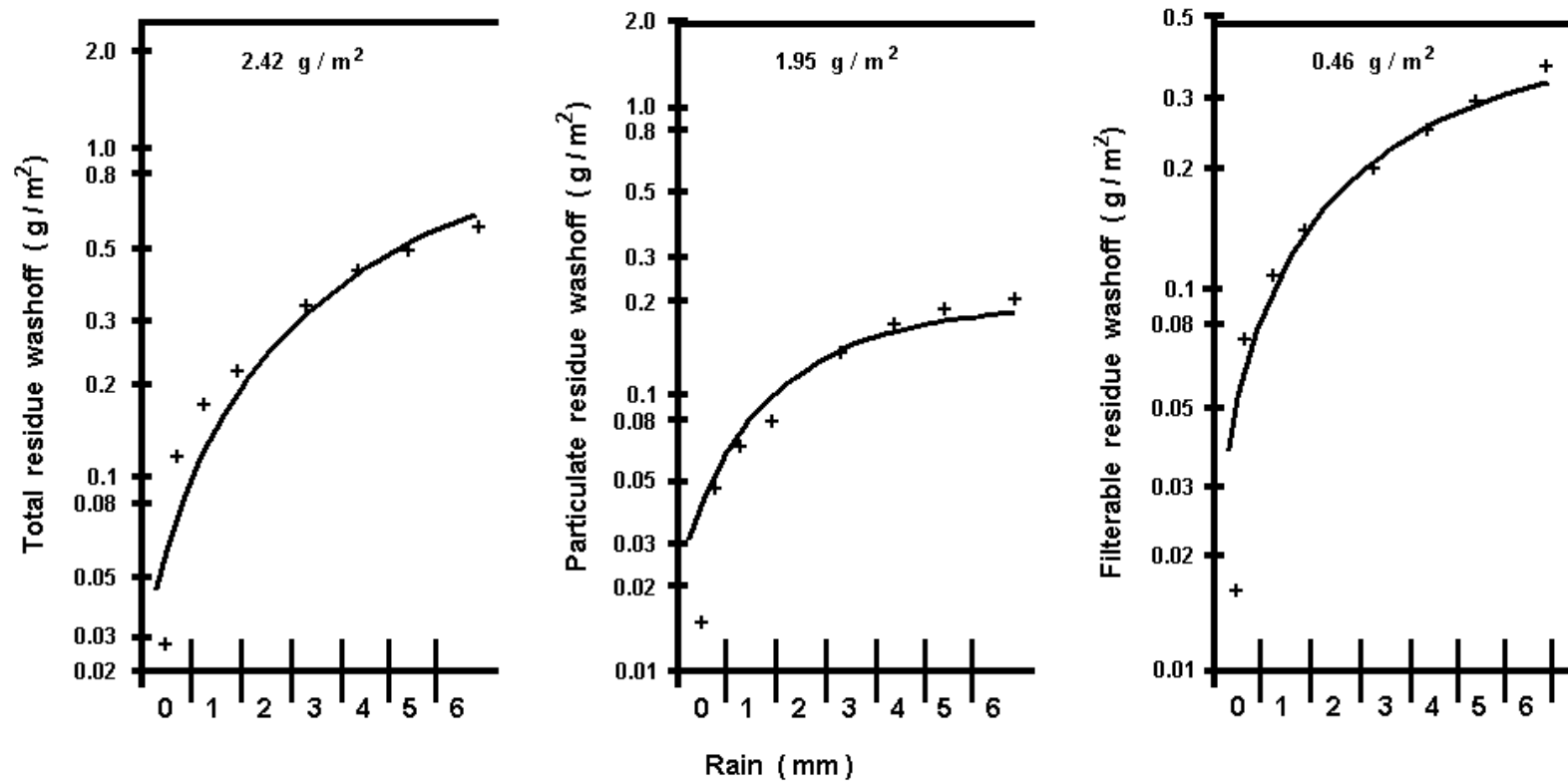


Figure 4-11. Washoff plots for LCS replicate test (light rain intensity, clean, and smooth street) (Pitt 1987).

Table 4-5. Suspended solids washoff coefficients (Pitt 1987)¹.

Test condition code	Rain intensity category	Street dirt loading category	Street texture category	Calculated k (1/hr)	Standard error for k (1/hr)	Ratio of available load to total initial load
HCR	high	clean	rough	0.832	0.064	0.11
LCR	low	clean	rough	0.344	0.038	0.061
HDR	high	dirty	rough	0.077	0.008	0.032
LDR	low	dirty	rough	0.619	0.052	0.028
HCS	high	clean	smooth	1.007	0.321	0.26
LCS	low	clean	smooth	0.302	0.024	0.047
HDS	high	dirty	smooth	0.167	0.015	0.13
LCS	low	clean	smooth	0.335	0.031	0.11

1) Note:

$$N = N_o e^{-kR}$$

where: N = residual street dirt load, after the rain (lb/curb-mile)

N_o = initial street dirt load (lb/curb-mile)

R = rain depth (inches)

k = proportionality constant (1/hr)

Observed Particle Size Distributions in Stormwater

The particle size distributions of stormwater greatly affect the ability of most controls to reduce pollutant discharges. This research included particle size analyses of 121 stormwater samples from three states that were not affected by stormwater controls (southern New Jersey as part of the inlet tests; Birmingham, AL as part of the MCTT pilot-scale tests; and in Milwaukee and Minocqua, WI, as part of the MCTT full-scale tests). These samples represented stormwater entering the stormwater controls being tested. Particle sizes were measured using a Coulter Multi-Sizer IIe and verified with microscopic, sieve, and settling column tests.

Figures 4-12 through 4-14 are grouped box and whisker plots showing the particle sizes (in μm) corresponding to the 10th, 50th (median) and 90th percentiles of the cumulative distributions. If 90% control of SS was desired, for example, then the particles larger than the 90th percentile would have to be removed. The median particle sizes ranged from 0.6 to 38 μm and averaged 14 μm . The 90th percentile sizes ranged from 0.5 to 11 μm and averaged 3 μm . These particle sizes are all substantially smaller than have been typically assumed for stormwater. In all cases, the New Jersey samples had the smallest particle sizes, followed by Wisconsin, and then Birmingham, AL, which had the largest particles. The New Jersey samples were obtained from gutter flows in a residential semi-xeroscaped neighborhood, the Wisconsin samples were obtained from several source areas, including parking areas and gutter flows mostly from residential,

but from some commercial areas, and the Birmingham samples were collected from a long-term parking area.

Atmospheric Sources of Urban Runoff Pollutants

Atmospheric processes affecting urban runoff pollutants include dry dustfall and precipitation quality. These have been monitored in many urban and rural areas. In many instances, however, the samples were combined as a bulk precipitation sample before processing. Automatic precipitation sampling equipment can distinguish between dry periods of fallout and precipitation. These devices cover and uncover appropriate collection jars exposed to the atmosphere. Much of this information has been collected as part of the Nationwide Urban Runoff Program (NURP) and the Atmospheric Deposition Program, both sponsored by the USEPA (EPA 1983a).

This information must be interpreted carefully, because of the ability of many polluted dust and dirt particles to be resuspended and then redeposited within the urban area. In many cases, the measured atmospheric deposition measurements include material that was previously residing and measured in other urban runoff pollutant source areas. Also, only small amounts of the atmospheric deposition material would directly contribute to runoff. Rain is subjected to infiltration and the dry fall particulates are likely mostly incorporated with surface soils and only small fractions are then eroded during rains. Therefore, mass balances and determinations of urban runoff deposition and accumulation from different source areas can be highly misleading, unless transfer of material between source areas and the effective yield of this material to the receiving water is considered. Depending on the land use, relatively little of the dustfall in urban areas likely contributes to stormwater discharges.

Dustfall and precipitation affect all of the major urban runoff source areas in an urban area. Dustfall, however, is typically not a major pollutant source but fugitive dust is mostly a mechanism for pollutant transport, as previously mentioned. Most of the dustfall monitored in an urban area is resuspended particulate matter from street surfaces or wind erosion products from vacant areas (Pitt 1979). Point source pollutant emissions can also significantly contribute to dustfall pollution, especially in industrial areas. Transported dust from regional agricultural activities can also significantly affect urban stormwater.

Wind transported materials are commonly called “dustfall.” Dustfall includes sedimentation, coagulation with subsequent sedimentation and impaction. Dustfall is normally measured by collecting dry samples, excluding rainfall and snowfall. If rainout and washout are included, one has a measure of total atmospheric fallout. This total atmospheric fallout is sometimes called “bulk precipitation.” Rainout removes

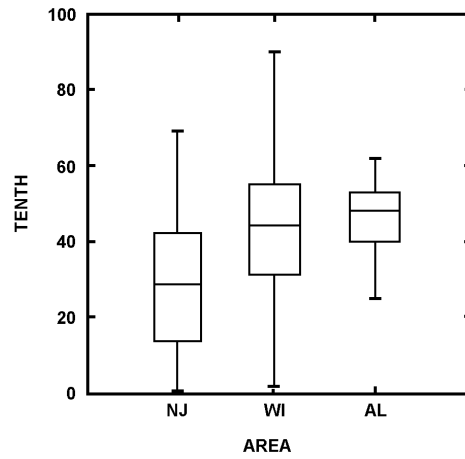


Figure 4-12. Tenth percentile particle sizes for stormwater inlet flows.

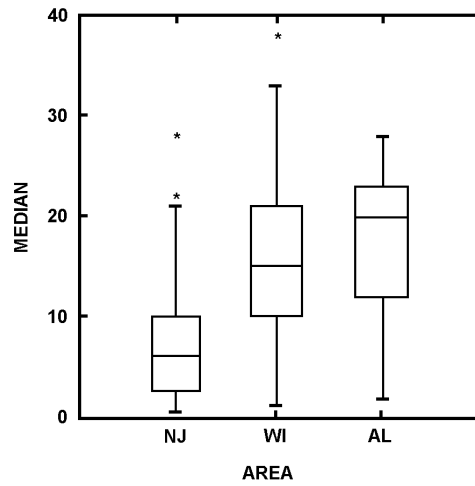


Figure 4-13. Fiftieth percentile particle sizes for stormwater inlet flows.

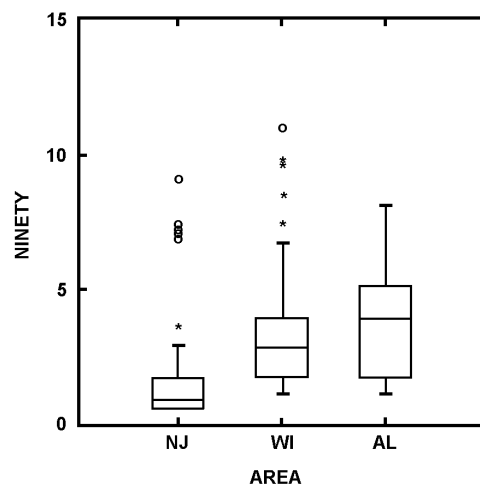


Figure 4-14. Ninetieth percentile particle sizes for stormwater inlet flows.

contaminants from the atmosphere by condensation processes in clouds, while washout is the removal of contaminants by the falling rain. Therefore, precipitation can include natural contamination associated with condensation nuclei in addition to collecting atmospheric pollutants as the rain or snow falls. In some areas, the contaminant contribution by dry deposition is small, compared to the contribution by precipitation (Malmquist 1978). However, in heavily urbanized areas, dustfall can contribute more of an annual load than the wet precipitation, especially when dustfall includes resuspended materials.

Table 4-6 summarizes rain quality reported by several researchers. As expected, the non-urban area rain quality can be substantially better than urban rain quality. Many of the important heavy metals, however, have not been detected in rain in many areas of the country. The most important heavy metals found in rain have been lead and zinc, both being present in rain in concentrations from about 20 µg/l up to several hundred µg/l. It is expected that more recent lead rainfall concentrations would be substantially less, reflecting the decreased use of leaded gasoline since these measurements were taken. Iron is also present in relatively high concentrations in rain (about 30 to 40 µg/l).

Table 4-6. Summary of reported rain quality.

	Rural-Northwest (Quilayute, WA) ¹	Rural-Northeast (Lake George, NY) ¹	Urban- Northwest (Lodi, NJ) ²	Urban- Midwest (Cincinnati, OH) ³	Other Urban ³	Continental Avg. (32 locations) ¹
Suspended solids, mg/l				13		
Volatile suspended solids, mg/l				3.8		
Inorganic nitrogen, mg/l as N				0.69		
Ammonia, mg/l as N					0.7	
Nitrates, mg/l as N					0.3	
Total phosphates, mg/l as P					<0.1	
Ortho phosphate, mg/l as P				0.24		
Scandium, µg/l	<0.002	nd				nd
Titanium, µg/l	nd	nd				nd
Vanadium, µg/l	nd	nd				nd
Chromium, µg/l	<2	nd	1			nd
Manganese, µg/l	2.6	3.4				12
Iron, µg/l	32	35				
Cobalt, µg/l	0.04	nd				nd
Nickel, µg/l	nd	nd	3			43
Copper, µg/l	3.1	8.2	6			21
Zinc, µg/l	20	30	44			107
Lead, µg/l			45			

1) Rubin 1976

2) Wilbur and Hunter 1980

3) Manning et al. 1976

The concentrations of various urban runoff pollutants associated with dry dustfall are summarized in Table 4-7. Urban, rural and oceanic dry dustfall samples contained more than 5,000 mg iron/kg total solids. Zinc and lead were present in high concentrations. These constituents can have concentrations of up to several thousand mg of pollutant per kg of dry dustfall. Spring et al. (1978) monitored dry dustfall near a major freeway in Los Angeles, CA. Based on a series of samples collected over several months, they found that lead concentrations on and near the freeway can be about 3,000 mg/kg, but as low as about 500 mg/kg 150 m (500 feet) away. In contrast, the chromium concentrations of the dustfall did not vary substantially between the two locations and approached oceanic dustfall chromium concentrations.

Table 4-7. Atmosphere dustfall quality.

Constituent, (mg constituent/kg total solids)	Urban ¹	Rural/ suburban ¹	Oceanic ¹	Near freeway (LA) ²	500' from freeway (LA) ²
pH				4.3	4.7
Phosphate-Phosphorous				1200	1600
Nitrate-Nitrogen, µg/l				5800	9000
Scandium, µg/l	5	3	4		
Titanium, µg/l	380	810	2700		
Vanadium, µg/l	480	140	18		
Chromium, µg/l	190	270	38	34	45
Manganese, µg/l	6700	1400	1800		
Iron, µg/l	24000	5400	21000		
Cobalt, µg/l	48	27	8		
Nickel, µg/l	950	1400			
Copper, µg/l	1900	2700	4500		
Zinc, µg/l	6700	1400	230		
Lead, µg/l				2800	550

1) Summarized by Rubin 1976

2) Spring 1978

Much of the monitored atmospheric dustfall and precipitation would not reach the urban runoff receiving waters. The percentage of dry atmospheric deposition retained in a rural watershed was extensively monitored and modeled in Oakridge, TN (Barkdoll et al. 1977). They found that about 98% of the lead in dry atmospheric deposits was retained in the watershed, along with about 95% of the cadmium, 85% of the copper, 60% of the chromium and magnesium and 75% of the zinc and mercury. Therefore, if the dry

deposition rates were added directly to the yields from other urban runoff pollutant sources, the resultant urban runoff loads would be very much overestimated.

Tables 4-8 and 4-9 report bulk precipitation (dry dustfall plus rainfall) quality and deposition rates as reported by several researchers. For the Knoxville, KY, area (Betson 1978), chemical oxygen demand (COD) was found to be the largest component in the bulk precipitation monitored, followed by filterable residue and nonfilterable residue. Table 4-9 also presents the total watershed bulk precipitation, as the percentage of the total stream flow output, for the three Knoxville watersheds studies. This shows that almost all of the pollutants presented in the urban runoff streamflow outputs could easily be accounted for by bulk precipitation deposition alone. Betson concluded that bulk precipitation is an important component for some of the constituents in urban runoff, but the transport and resuspension of particulates from other areas in the watershed are overriding factors.

Rubin (1976) stated that resuspended urban particulates are returned to the earth's surface and waters in four main ways: gravitational settling, impaction, precipitation and washout. Gravitational settling, as dry deposition, returns most of the particles. This not only involves the settling of relatively large fly ash and soil particles, but also the settling of smaller particles that collide and coagulate. Rubin stated that particles that are less than 0.1 μm in diameter move randomly in the air and collide often with other particles. These small particles can grow rapidly by this coagulation process. These small particles would soon be totally depleted in the air if they were not constantly replenished. Particles in the 0.1 to 1.0 μm range are also removed primarily by coagulation. These larger particles grow more slowly than the smaller particles because they move less rapidly in the air, are somewhat less numerous and, therefore, collide less often with other particles. Particles with diameters larger than 1 μm have appreciable settling velocities. Those particles about 10 μm in diameter can settle rapidly, although they can be kept airborne for extended periods of time and for long distances by atmospheric turbulence.

The second important particulate removal process from the atmosphere is impaction. Impaction of particles near the earth's surface can occur on vegetation, rocks and building surfaces. The third form of particulate removal from the atmosphere is precipitation, in the form of rain and snow. This is caused by the rainout process where the particulates are removed in the cloud-forming process. The fourth important removal process is washout of the particulates below the clouds during the precipitation event. Therefore, it is easy to see that re-entrained particles (especially from street surfaces, other paved surfaces, rooftops and from soil erosion) in urban areas can be readily redeposited through these various processes, either close to the points of origin or at some distance away.

Pitt (1979) monitored airborne concentrations of particulates near typical urban roads. He found that on a number basis, the downwind roadside particulate concentrations were about 10% greater than upwind conditions. About 80% of the concentration

increases, by number, were associated with particles in the 0.5 to 1.0 μm size range. However, about 90% of the particle concentration increases by weight were associated with particles greater than 10 μm . Pitt found that the rate of particulate resuspension from street surfaces increases when the streets are dirty (cleaned infrequently) and varied widely for different street and traffic conditions. The resuspension rates were calculated based upon observed long-term accumulation conditions on street surfaces for many different study area conditions, and varied from about 0.30 to 3.6 kg per curb-km (one to 12 lb per curb-mile) of street per day.

Table 4-8. Bulk precipitation quality.

Constituent (all units mg/l except pH)	Urban (average of Knoxville St. Louis & Germany) ¹	Rural (Tennessee) ¹	Urban (Guteburg, Sweden) ²
Calcium	3.4	0.4	
Magnesium	0.6	0.1	
Sodium	1.2	0.3	
Chlorine	2.5	0.2	
Sulfate	8.0	8.4	
pH	5.0	4.9	
Organic Nitrogen	2.5	1.2	
Ammonia Nitrogen	0.4	0.4	2
Nitrite plus Nitrate-N	0.5	0.4	1
Total phosphate	1.1	0.8	0.03
Potassium	1.8	0.6	
Total iron	0.8	0.7	
Manganese	0.03	0.05	
Lead	0.03	0.01	0.05
Mercury	0.01	0.0002	
Nonfilterable residue	16		
Chemical Oxygen Demand	65		10
Zinc			0.08
Copper			0.02

1) Betson 1978

2) Malmquist 1978

Table 4-9. Urban bulk precipitation deposition rates (Betson 1978)¹.

Rank	Constituent	Average Bulk Deposition Rate (kg/ha/yr)	Average Bulk Prec. as a % of Total Streamflow Output
1	Chemical oxygen demand	530	490
2	Filterable residue	310	60
3	Nonfilterable residue	170	120
4	Alkalinity	150	120
5	Sulfate	96	470
6	Chloride	47	360
7	Calcium	38	170
8	Potassium	21	310
9	Organic nitrogen	17	490
10	Sodium	15	270
11	Silica	11	130
12	Magnesium	9	180
13	Total Phosphate	9	130
14	Nitrite and Nitrate-N	5.7	360
15	Soluble phosphate	5.3	170
16	Ammonia Nitrogen	3.2	1,100
17	Total Iron	1.9	47
18	Fluoride	1.8	300
19	Lead	1.1	650
20	Manganese	0.54	270
21	Arsenic	0.07	720
22	Mercury	0.008	250

1) Average for three Knoxville, KY, watersheds.

Murphy (1975) described a Chicago study where airborne particulate material within the city was microscopically examined, along with street surface particulates. The particulates from both of these areas were found to be similar (mostly limestone and quartz) indicating that the airborne particulates were most likely resuspended street surface particulates, or were from the same source.

PEDCo (1977) found that the re-entrained portion of the traffic-related particulate emissions (by weight) is an order of magnitude greater than the direct emissions

accounted for by vehicle exhaust and tire wear. They also found that particulate resuspensions from a street are directly proportional to the traffic volume and that the suspended particulate concentrations near the streets are associated with relatively large particle sizes. The medium particle size found, by weight, was about 15 μm , with about 22% of the particulates occurring at sizes greater than 30 μm . These relatively large particle sizes resulted in substantial particulate fallout near the road. They found that about 15% of the resuspended particulates fall out at 10 m, 25% at 20 m, and 35% at 30 m from the street (by weight).

In a similar study Cowherd et al. (1977) reported a wind erosion threshold value of about 5.8 m/s (13 mph). At this wind speed, or greater, significant dust and dirt losses from the road surface could result, even in the absence of traffic-induced turbulence. Rolfe and Reinbold (1977) also found that most of the particulate lead from automobile emissions settled out within 100 m of roads. However, the automobile lead does widely disperse over a large area. They found, through multi-elemental analyses, that the settled outdoor dust collected at or near the curb was contaminated by automobile activity and originated from the streets.

Source Area Sheetflow and Particulate Quality

This section summarizes the source area sheetflow and particulate quality data obtained from several studies conducted in California, Washington, Nevada, Wisconsin, Illinois, Ontario, Colorado, New Hampshire, and New York since 1979. Most of the data obtained were for street dirt chemical quality, but a relatively large amount of parking and roof runoff quality data have also been obtained. Only a few of these studies evaluated a broad range of source areas or land uses.

Source Area Particulate Quality

Particulate potency factors (usually expressed as mg pollutant/kg dry particulate residue) for many samples are summarized on Tables 4-10 and 4-11. These data can help recognize critical source areas, but care must be taken if they are used for predicting runoff quality because of likely differential effects due to washoff and erosion from the different source areas. These data show the variations in chemical quality between particles from different land uses and source areas. Typically, the potency factors increase as the use of an area becomes more intensive, but the variations are slight for different locations throughout the country. Increasing concentrations of heavy metals with decreasing particle sizes was also evident, for those studies that included particle size information. Only the quality of the smallest particle sizes are shown on these tables because they best represent the particles that are removed during rains.

Warm Weather Sheetflow Quality

Sheetflow data, collected during actual rain, are probably more representative of runoff conditions than the previously presented dry particulate quality data because they are not further modified by washoff mechanisms. These data, in conjunction with source area flow quantity information, can be used to predict outfall conditions and the magnitude of the relative sources of critical pollutants. Tables 4-12 through 4-15

summarize warm weather sheetflow observations, separated by source area type and land use, from many locations. The major source area categories are listed below:

1. Roofs
2. Paved parking areas
3. Paved storage areas
4. Unpaved parking and storage areas
5. Paved driveways
6. Unpaved driveways
7. Dirt walks
8. Paved sidewalks
9. Streets
10. Landscaped areas
11. Undeveloped areas
12. Freeway paved lanes and shoulders

Toronto warm weather sheetflow water quality data were plotted against the rain volume that had occurred before the samples were collected to identify any possible trends of concentrations with rain volume (Pitt and McLean 1986). The street runoff data obtained during the special washoff tests reported earlier were also compared with the street sheetflow data obtained during the actual rain events (Pitt 1987). These data observations showed definite trends of solids concentrations verses rain volume for most of the source area categories. Sheetflows from all pervious areas combined had the highest total solids concentrations from any source category, for all rain events. Other paved areas (besides streets) had total solids concentrations similar to runoff from smooth industrial streets. The concentrations of total solids in roof runoff were almost constant for all rain events, being slightly lower for small rains than for large rains. No other pollutant, besides SS, had observed trends of concentrations with rain depths for the samples collected in Toronto. Lead and zinc concentrations were highest in sheetflows from paved parking areas and streets, with some high zinc concentrations also found in roof drainage samples. High bacteria populations were found in sidewalk, road, and some bare ground sheetflow samples (collected from locations where dogs would most likely be "walked").

Some of the Toronto sheetflow contributions were not sufficient to explain the concentrations of some constituents observed in runoff at the outfall. High concentrations of dissolved chromium, dissolved copper, and dissolved zinc in a Toronto industrial outfall during both wet and dry weather could not be explained by wet weather sheetflow observations (Pitt and McLean 1986). As an example, very few detectable chromium observations were obtained in any of the more than 100 surface sheetflow samples analyzed. Similarly, most of the fecal coliform populations observed in sheetflows were significantly lower than those observed at the outfall, especially during snowmelt. It is expected that some industrial wastes, possibly originating from metal plating operations, were the cause of these high concentrations of dissolved

metals at the outfall and that some sanitary sewage was entering the storm drainage system.

Table 4-15 summarizes the very little filterable pollutant concentration data available, before this EPA project, for different source areas. Most of the available data are for residential roofs and commercial parking lots.

Table 4-10. Summary of observed street dirt mean chemical quality (mg constituent/kg solids).

Constituent	Residential	Commercial	Industrial
P	620 (4) 540 (6) 1100 (5) 710 (1) 810 (3)	400 (6) 1500 (5) 910 (1)	670 (4)
TKN	1030 (4) 3000 (6) 290 (5) 2630 (3) 3000 (2)	1100 (6) 340 (5) 4300 (2)	560 (4)
COD	100,000 (4) 150,000 (6) 180,000 (5) 280,000 (1) 180,000 (3) 170,000 (2)	110,000 (6) 250,000 (5) 340,000 (1) 210,000 (2)	65,000 (4)
Cu	162 (4) 110 (6) 420 (2)	130 (6) 220 (2)	360 (4)
Pb	1010 (4) 1800 (6) 530 (5) 1200 (1) 1650 (3) 3500 (2)	3500 (6) 2600 (5) 2400 (1) 7500 (2)	900 (4)
Zn	460 (4) 260 (5) 325 (3) 680 (2)	750 (5) 1200 (2)	500 (4)
Cd	<3 (5) 4 (2)	5 (5) 5 (2)	
Cr	42 (4) 31 (5) 170 (2)	65 (5) 180 (2)	70 (4)

References; location; particle size described:

- (1) Bannerman et al. 1983 (Milwaukee, WI) <31µm
- (2) Pitt 1979 (San Jose, CA) <45 µm
- (3) Pitt 1985 (Bellevue, WA) <63 µm
- (4) Pitt and McLean 1986 (Toronto, Ontario) <125 µm
- (5) Pitt and Sutherland 1982 (Reno/Sparks, NV) <63 µm
- (6) Terstriep et al. 1982 (Champaign/Urbana, IL) >63 µm

Table 4-11. Summary of observed particulate quality for other source areas (means for <125 µm particles) (mg constituent/kg solids).

	P	TKN	COD	Cu	Pb	Zn	Cr
Residential/Commercial Land Uses							
	1500	5700	240,000	130	980	1900	77
Roofs	600	790	78,000	145	630	420	47
Paved parking	400	850	50,000	45	160	170	20
Unpaved driveways	550	2750	250,000	170	900	800	70
Paved driveways	360	760	25,000	15	38	50	25
Dirt footpath	1100	3620	146,000	44	1200	430	32
Paved sidewalk	1300	1950	70,000	30	50	120	35
Garden soil	870	720	35,000	35	230	120	25
Road shoulder							
Industrial Land Uses							
Paved parking	770	1060	130,000	1110	650	930	98
Unpaved parking/storage	620	700	110,000	1120	2050	1120	62
Paved footpath	890	1900	120,000	280	460	1300	63
Bare ground	700	1700	70,000	91	135	270	38

Source: Pitt and McLean 1986 (Toronto, Ontario)

Table 4-12. Sheetflow quality summary for other source areas (mean concentration and source of data).

Pollutant and Land Use	Roofs	Paved Parking	Paved Storage	Unpaved Parking/Storage	Paved Driveways	Unpaved Driveways	Dirt Walks	Paved Sidewalks	Streets
<u>Total Solids (mg/l)</u>									
Residential:	58 (5) 64 (1) 18 (4)	1790 (5)	73 (5)		510 (5)		1240 (5)	49 (5)	325 (5) 235 (4)
Commercial:	95 (1) 190 (4)	340 (2) 240 (1) 102 (7)							325 (4)
Industrial:	113 (5)	490 (5)	270 (5)	1250 (5)	506 (5)	5620 (5)		580 (5)	1800 (5)
<u>Suspended Solids (mg/l)</u>									
Residential:	22 (1) 13 (5)	1660 (5)	41 (5)		440 (5)		810 (5)	20 (5)	242 (5)
Commercial:		270 (2) 65 (1) 41 (7)							242 (5)
Industrial:	4 (5)	306 (5)	202 (5)	730 (5)	373 (5)	4670 (5)		434 (5)	1300 (5)
<u>Dissolved Solids (mg/l)</u>									
Residential:	42 (10) 5 (5)	130 (5)	32 (5)		70 (5)		430 (5)	29 (5)	83 (5) 83 (4)
Commercial:		70 (2) 175 (1) 61 (7)							83 (5)
Industrial:	109 (5)	184 (5)	68 (5)	520 (5)	133 (5)	950 (5)		146 (5)	500 (5)

Table 4-12. Sheetflow quality summary for other source areas (mean concentration and source of data) (Continued).

Pollutant and Land Use	Roofs	Paved Parking	Paved Storage	Unpaved Parking/Storage	Paved Driveways	Unpaved Driveways	Dirt Walks	Paved Sidewalks	Streets
<u>BOD₅ (mg/l)</u>									
Residential:	3 (4)	22 (4)							13 (4)
Commercial:	7 (4)	11 (1) 4 (8)							
<u>COD (mg/l)</u>									
Residential:	46 (5) 27 (1) 20 (4)	173 (5)	22 (5)		178 (5)			62 (5)	174 (5) 170 (4)
Commercial:	130 (4)	190 (2) 180 (4) 53 (1) 57 (8)							174 (5)
Industrial:	55 (5)	180 (5)	82 (5)	247 (5)	138 (5)	418 (5)		98 (5)	322 (5)
<u>Total Phosphorus (mg/l)</u>									
Residential:	0.03 (5) 0.05 (1) 0.1 (4)				0.36 (5)		0.20 (5)	0.80 (5)	0.62 (5) 0.31 (4)
Commercial:	0.03 (4) 0.07 (4)	0.16 (1) 0.15 (7) 0.73 (5) 0.9 (2) 0.5 (4)							0.62 (5)
Industrial:	<0.06 (5)	2.3 (5)	0.7 (5)	1.0 (5)	0.9 (5)	3.0 (5)		0.82 (5)	1.6 (5)

Table 4-12. Sheetflow quality summary for other source areas (mean concentration and source of data) (Continued).

Pollutant and Land Use	Roofs	Paved Parking	Paved Storage	Unpaved Parking/Storage	Paved Driveways	Unpaved Driveways	Dirt Walks	Paved Sidewalks	Streets
<u>Total Phosphate (mg/l)</u>									
Residential:	<0.04 (5) 0.08 (4)				<0.2 (5)		0.66 (5)	0.64 (5)	0.07 (5) 0.12 (4)
Commercial:	0.02 (4)	0.03 (5) 0.3 (2) 0.5 (4) 0.04 (7) 0.22 (8)	<0.02 (5)						0.07 (5)
Industrial:	<0.02 (5)	0.6 (5)	0.06 (5)	0.13 (5)	<0.02 (5)	0.10 (5)		0.03 (5)	0.15 (5)
<u>TKN (mg/l)</u>									
Residential:	1.1 (5) 0.71 (4)				3.1 (5)		1.3 (5)	1.1 (5)	2.4 (5) 2.4 (4)
Commercial:	4.4 (4)	3.8 (5) 4.1 (2) 1.5 (4) 1.0 (1) 0.8 (8)							2.4 (5)
Industrial:	1.7 (5)	2.9 (5)	3.5 (5)	2.7 (5)	5.7 (5)	7.5 (5)		4.7 (5)	5.7 (5)
<u>Ammonia (mg/l)</u>									
Residential:	0.1 (5) 0.9 (1) 0.5 (4)	0.1 (5)	0.3 (5)		<0.1 (5)		0.5 (5)	0.3 (5)	<0.1 (5) 0.42 (4)
Commercial:	1.1 (4)	1.4 (2) 0.35 (4) 0.38 (1)							<0.1 (5)
Industrial:	0.4 (5)	0.3 (5)	0.3 (5)	<0.1 (5)	<0.1 (5)	<0.1 (5)		<0.1 (5)	<0.1 (5)

Table 4-12. Sheetflow quality summary for other source areas (mean concentration and source of data) (Continued).

Pollutant and Land Use	Roofs	Paved Parking	Paved Storage	Unpaved Parking/Storage	Paved Driveways	Unpaved Driveways	Dirt Walks	Paved Sidewalks	Streets
<u>Phenols (mg/l)</u>									
Residential:	2.4 (5)	12.2 (5)	30.0 (5)		9.7 (5)		<0.4 (5)	8.6 (5)	6.2 (5)
Industrial:	1.2 (5)	9.4 (5)	2.6 (5)	8.7 (5)	7.0 (5)	7.4 (5)		8.7 (5)	24 (7)
<u>Aluminum (µg/l)</u>									
Residential:	0.4 (5)	3.2 (5)	0.38 (5)		5.3 (5)		<0.03 (5)	0.5 (5)	1.5 (5)
Industrial:	<0.2 (5)	3.5 (5)	3.1 (5)	9.2 (5)	3.4 (5)	41 (5)		1.2 (5)	14 (5)
<u>Cadmium (µg/l)</u>									
Residential:	<4 (5) 0.6 (1)	2 (5)	<5 (5)		5 (5)		<1 (5)	<4 (5)	<5 (5)
Commercial:		5.1 (7) 0.6 (8)							<5 (5)
Industrial:	<4 (5)	<4 (5)	<4 (5)	<4 (5)	<4 (5)	<4 (5)		<4 (5)	<4 (5)
<u>Chromium (µg/l)</u>									
Residential:	<60 (5) <5 (4)	20 (5) 71 (4)	<10 (5)		<60 (5)		<10 (5)	<60 (5)	<60 (5) 49 (4)
Commercial:	<5 (4)	19 (7) 12 (8)							<60 (5)
Industrial:	<60 (5)	<60 (5)	<60 (5)	<60 (5)	<60 (5)	70 (5)		<60 (5)	<60 (5)

Table 4-12. Sheetflow quality summary for other source areas (mean concentration and source of data) (Continued).

Pollutant and Land Use	Roofs	Paved Parking	Paved Storage	Unpaved Parking/Storage	Paved Driveways	Unpaved Driveways	Dirt Walks	Paved Sidewalks	Streets
<u>Copper (ug/l)</u>									
Residential:	10 (5) <5 (4)	100 (5)	20 (5)		210 (5)		20 (5)	20 (5)	40 (5) 30 (4)
Commercial:	110 (4)	40 (2) 46 (4) 110 (7)							40 (5)
Industrial:	<20 (5)	480 (5)	260 (5)	120 (5)	40 (5)	140 (5)		30 (5)	220 (5)
<u>Lead (ug/l)</u>									
Residential:	<40 (5) 30 (3) 48 (1) 17 (4)	250 (5)	760 (5)		1400 (5)		30 (5)	80 (5)	180 (5) 670 (4)
Commercial:	19 (4) 30 (1)	200 (2) 350 (3) 1090 (4) 146 (1) 255 (7) 54 (8)							180 (5)
Industrial:	<40 (5)	230 (5)	280 (5)	210 (5)	260 (5)	340 (5)		<40 (5)	560 (5)

Table 4-12. Sheetflow quality summary for other source areas (mean concentration and source of data) (Continued).

Pollutant and Land Use	Roofs	Paved Parking	Paved Storage	Unpaved Parking/Storage	Paved Driveways	Unpaved Driveways	Dirt Walks	Paved Sidewalks	Streets
<u>Zinc (µg/l)</u>									
Residential:	320 (5) 670 (1) 180 (4)	520 (5)	390 (5)		1000 (5)		40 (5)	60 (5)	180 (5) 140 (4)
Commercial:	310 (1) 80 (4)	300 (5) 230 (4) 133 (1) 490 (7)							180 (5)
Industrial:	70 (5)	640 (7)	310 (5)	410 (5)	310 (5)	690 (5)		60 (5)	910 (5)

References:

- (1) Bannerman et al. 1983 (Milwaukee, WI) (NURP)
- (2) Denver Regional Council of Governments 1983 (NURP)
- (3) Pitt 1983 (Ottawa)
- (4) Pitt and Bozeman 1982 (San Jose)
- (5) Pitt and McLean 1986 (Toronto)
- (7) STORET Site #590866-2954309 (Shop-Save-Durham, NH) (NURP)
- (8) STORET Site #596296-2954843 (Huntington-Long Island, NY) (NURP)

Table 4-13. Sheetflow quality summary for undeveloped landscaped and freeway pavement areas (mean observed concentrations and source of data).

Pollutants	Landscaped Areas	Undeveloped Areas	Freeway Paved Lane and Shoulder Areas
Total Solids, mg/l	388 (4)	588 (4)	340 (5)
Suspended Solids, mg/l	100 (4)	400 (1) 390 (4)	180 (5)
Dissolved Solids, mg/l	288 (4)	193 (4)	160 (5)
BOD ₅ , mg/l	3 (3)	----	10 (5)
COD, mg/l	70 (3) 26 (4)	72 (1) 54 (4)	130 (5)
Total Phosphorus, mg/l	0.42 (3) 0.56 (4)	0.40 (1) 0.68 (4)	----
Total Phosphate, mg/l	0.32 (3) 0.14 (4)	0.10 (1) 0.26 (4)	0.38 (5)
TKN, mg/l	1.32 (3) 3.6 (4)	2.9 (1) 1.8 (4)	2.5 (5)
Ammonia, mg/l	1.2 (3) 0.4 (4)	0.1 (1) <0.1 (4)	----
Phenols, µg/l	0.8 (4)	----	----
Aluminum, µg/l	1.5 (4)	11 (4)	----
Cadmium, µg/l	<3 (4)	<4 (4)	60 (5)
Chromium, µg/l	10 (3)	<60 (4)	70 (5)
Copper, µg/l	<20 (4)	40 (1) 31 (3) <20 (4)	120 (5)
Lead, µg/l	30 (2) 35 (3) <30 (4)	100 (1) 30 (2) <40 (4)	2000 (5)
Zinc, µg/l	10 (3)	100 (1) 100 (4)	460 (5)

References:

- (1) Denver Regional Council of Governments 1983 (NURP)
- (2) Pitt 1983 (Ottawa)
- (3) Pitt and Bozeman 1982 (San Jose)
- (4) Pitt and McLean 1986 (Toronto)
- (5) Shelly and Gaboury 1986 (Milwaukee)

Table 4-14. Source area bacteria sheetflow quality summary (means).

Pollutant and Land Use	Roofs	Paved Parking	Paved Storage	Unpaved Parking/Storage	Paved Driveways	Unpaved Driveways	Dirt Walks	Paved Sidewalks	Streets	Land-scaped	Un-developed	Freeway Paved Lane and Shoulders
Fecal Coliforms (#/100 ml)												
Residential:	85 (2) <2 (3) 1400 (4)	250,000 (4)	100 (4)		600 (4)			11,000 (4)	920 (3) 6,900 (4)	3300 (4)	5400 (2) 49 (3)	1500 (7)
Commercial	9 (3)	2900 (2) 350 (3) 210 (1) 480 (5) 23,000 (6)										
Industrial:	1600 (4)	8660 (6)	9200 (4)	18,000 (4)	66,000 (4)	300,000 (4)		55,000 (4)	100,000 (4)			
Fecal Strep (#/100 ml)												
Residential:	170 (2) 920 (3) 2200 (4)	190,000 (4)	<100 (4)		1900 (4)		1800 (4)		>2400 (3) 7300 (4)	43,000 (4)	16,500 (2) 920 (3)	2200 (7)
Commercial:	17 (2)	11,900 (2) >2400 (3) 770 (1) 1120 (5) 62,000 (6)										
Industrial:	690 (4)	7300 (4)	2070 (4)	8100 (4)	36,000 (4)	21,000 (4)		3600 (4)	45,000 (4)			
Pseudo, Aerug (#/100 ml)												
Residential:	30,000 (4) 50 (4)	1900 (4)	100 (4)		600 (4)		600 (4)		570 (4)	2100 (4)		
Industrial:		5800 (4)	5850 (4)	14,000 (4)	14,300 (4)	100 (4)		3600 (4)	6200 (4)			

References:

- | | |
|--|---|
| (1) Bannerman et al. 1983 (Milwaukee, WI) (NURP) | (5) STORET Site #590866-2954309 (Shop-Save-Durham, NH) (NURP) |
| (2) Pitt 1983 (Ottawa) | (6) STORET Site #596296-2954843 (Huntington-Long Island, NY) (NURP) |
| (3) Pitt and Bozeman 1982 (San Jose) | (7) Kobriger et al. 1981 and Gupta et al. 1977 |
| (4) Pitt and McLean 1986 (Toronto) | |

Table 4-15. Source area filterable pollutant concentration summary (means).

	Residential			Commercial			Industrial		
	Total	Filterable	Filterable (%)	Total	Filterable	Filterable (%)	Total	Filterable	Filt. (%)
Roof Runoff									
Solids (mg/l)	64 58	42 45	66 (1) 77 (3)				113	110	97 (3)
Phosphorus (mg/l)	0.054	0.013	24 (1)						
Lead (µg/l)	48	4	8 (1)						
Paved Parking									
Solids (mg/l)				240 102 1790	175 61 138	73 (1) 60 (4) 8 (3)	490	138	28 (3)
Phosphorus (mg/l)				0.16 0.9	0.03 0.3	19 (1) 33 (2)			
TKN (mg/l)				0.77	0.48	62 (5)			
Lead (µg/l)				146 54	5 8.8	3 (1) 16 (5)			
Arsenic (µg/l)				0.38	0.095	25 (5)			
Cadmium (µg/l)				0.62	0.11	18 (5)			
Chromium (µg/l)				11.8	2.8	24 (5)			
Paved Storage									
Solids (mg/l)				73	32	44 (3)	270	64	24 (3)

References:

- (1) Bannerman et al. 1983 (Milwaukee) (NURP)
- (2) Denver Regional Council of Governments 1983 (NURP)
- (3) Pitt and McLean 1986 (Toronto)
- (4) STORET Site #590866-2954309 (Shop-Save-Durham, NH) (NURP)
- (6) STORET Site #596296-2954843 (Huntington-Long Island, NY) (NURP)

Other Pollutant Contributions to the Storm Drainage System

The detection of pentachlorophenols in the relatively few samples previously analyzed indicated important leaching from treated wood. Frequent detections of polycyclic aromatic hydrocarbons (PAHs) during the U.S. Environmental Protection Agency's Nationwide Urban Runoff Program (EPA 1983a) may possibly indicate leaching from creosote treated wood, in addition to fossil fuel combustion sources. High concentrations of copper, and some chromium and arsenic observations also indicate the potential of leaching from "CCA" (copper, chromium, and arsenic) treated wood.

The significance of these leachate products in the receiving waters is currently unknown, but alternatives to these preservatives should be considered. Many cities use aluminum and concrete utility poles instead of treated wood poles. This is especially important considering that utility poles are usually located very close to the drainage system ensuring an efficient delivery of leachate products. Many homes currently use wood stains containing pentachlorophenol and other wood preservatives. Similarly, the construction of retaining walls, wood decks and playground equipment with treated wood is common. Some preservatives (especially creosote) cause direct skin irritation, besides contributing to potential problems in receiving waters. Many of these wood products are at least located some distance from the storm drainage system, allowing some improvement to surface water quality by infiltration through pervious surfaces.

Sources of Stormwater Toxicants

This project included the collection and analysis of 87 urban stormwater runoff samples from a variety of source areas under different rain conditions as summarized in Table 4-16. All of the samples were analyzed in filtered (0.45 µm filter) and non-filtered forms to enable partitioning of the toxicants into "particulate" (non-filterable) and "dissolved" (filterable) forms.

Table 4-16. Numbers of samples collected from each source area type.

Local Source Areas ¹	Residential	Commercial/ Institutional	Industrial	Mixed
Roofs	5	3	4	
Parking Areas	2	11	3	
Storage Areas	na	2	6	
Streets	1	1	4	
Loading Docks	na	na	3	
Vehicle Service Area	na	5	na	
Landscaped Areas	2	2	2	
Urban Creeks				19
Detention Ponds				12

1) All collected in Birmingham, AL.

Analyses and Sampling

The samples listed in Table 4-16 were all obtained from the Birmingham, AL, area. Samples were taken from shallow flows originating from homogeneous source areas by using several manual grab sampling procedures. For deep flows, samples were collected directly into the sample bottles. For shallow flows, a peristaltic hand operated vacuum pump created a small vacuum in the sample bottle, which then gently drew the sample directly into the container through a Teflon™ tube. About one liter of sample was needed, split into two containers: one 500 ml glass bottle with Teflon™ lined lid was used for the organic and toxicity analyses and another 500 ml polyethylene bottle was used for the metal and other analyses.

An important aspect of the research was to evaluate the effects of different land uses and source areas, plus the effects of rain characteristics, on sample toxicant concentrations. Therefore, careful records were obtained of the amount of rain and the rain intensity that occurred before the samples were obtained. Antecedent dry period data were also obtained to compare with the chemical data in a series of statistical tests.

All samples were handled, preserved, and analyzed according to accepted protocols (EPA 1982 and 1983b). The organic pollutants were analyzed using two gas chromatographs, one with a mass selective detector (GC/MSD) and another with an electron capture detector (GC/ECD). The pesticides were analyzed according to EPA method 505, while the base neutral compounds were analyzed according to EPA method 625 (but only using 100 ml samples). The pesticides were analyzed on a Perkin Elmer Sigma 300 GC/ECD using a J&W DB-1 capillary column (30m by 0.32 mm ID with a 1 µm film thickness). The base neutrals were analyzed on a Hewlett Packard 5890 GC with a 5970 MSD using a Supelco DB-5 capillary column (30m by 0.25 mm ID with a 0.2 µm film thickness). Table 4-17 lists the organic toxicants that were analyzed.

Metallic toxicants, also listed in Table 4-17, were analyzed using a graphite furnace equipped atomic absorption spectrophotometer (GFAA). EPA methods 202.2 (Al), 213.2 (Cd), 218.2 (Cr), 220.2 (Cu), 239.2 (Pb), 249.2 (Ni), and 289.2 (Zn) were followed in these analyses. A Perkin Elmer 3030B atomic absorption spectrophotometer was used after nitric acid digestion of the samples. Previous research (Pitt and McLean 1986; EPA 1983a) indicated that low detection limits were necessary in order to measure the filtered sample concentrations of the metals, which would not be achieved by use of a standard flame atomic absorption spectrophotometer. Low detection limits would enable partitioning of the metals between the solid and liquid phases to be investigated, an important factor in assessing the fates of the metals in receiving waters and in treatment processes.

Table 4-17. Toxic pollutants analyzed in samples.

Pesticides Detention Limit = 0.3 µg/l	Phthalate Esters Detention Limit = 0.5 µg/l	Polycyclic Aromatic Hydrocarbons Detention Limit = 0.5 µg/l		Metals Detention Limit = 1 µg/l
BHC (Benzene hexachloride)	Bis(2-ethylhexyl) Phthalate	Acenaphthene	Fluoranthene	Aluminum
Heptachlor	Butyl benzyl phthalate	Acenaphthylene	Fluorene	Cadmium
Aldrin	Di-n-butyl phthalate	Anthracene	Indeno (1,2,3-cd) pyrene	Chromium
Endosulfan	Diethyl phthalate	Benzo (a) anthracene	Naphthalene	Copper
Heptachlor epoxide	Dimethyl phthalate	Benzo (a) pyrene	Phenanthrene	Lead
DDE (Dichlorodiphenyl dichloroethylene)	Di-n-octyl phthalate	Benzo (b) fluoranthene	Pyrene	Nickel
DDD (Dichlorodiphenyl dichloroethane)		Benzo (ghi) perylene		Zinc
DDT (Dichlorodiphenyl trichloroethane)		Benzo (k) fluoranthene		
Endrin		Chrysene		
Chlordane		Dibenzo (a,h) anthracene		

The Microtox™ 100% sample toxicity screening test, from Azur Environmental (previously Microbics, Inc.), was selected for this research after comparisons with other laboratory bioassay tests. During the first research, 20 source area stormwater samples and combined sewer samples (obtained during a cooperative study being conducted in New York City) were split and sent to four laboratories for analyses using 14 different bioassay tests. Conventional bioassay tests were conducted using freshwater organisms at the EPA's Duluth, MN, laboratory and using marine organisms at the EPA's Narragansett Bay, RI, laboratory. In addition, other bioassay tests, using bacteria, were also conducted at the Environmental Health Sciences Laboratory at Wright State University, Dayton, OH. The tests represented a range of organisms that included fish, invertebrates, plants, and microorganisms.

The conventional bioassay tests conducted simultaneously with the Microtox™ screening test for the 20 stormwater sheetflow and combined sewer overflow (CSO) samples were all short-term tests. However, some of the tests were indicative of chronic toxicity (e.g., life cycle tests and the marine organism sexual reproduction tests), whereas the others would be classically considered as indicative of acute toxicity (e.g., Microtox™ and the fathead minnow tests). The following list shows the major tests that were conducted by each participating laboratory:

1. University of Alabama at Birmingham, Environmental Engineering Laboratory
Microtox™ bacterial luminescence tests (10-, 20-, and 35-minute exposures)
using the marine *Photobacterium phosphoreum*.

2. Wright State University, Biological Sciences Department
Macrofaunal toxicity tests:
Daphnia magna (water flea) survival; *Lemna minor* (duckweed) growth;
and *Selenastrum capricornutum* (green alga) growth.
Microbial activity tests (bacterial respiration):
Indigenous microbial electron transport activity;
Indigenous microbial inhibition of β -galactosidase activity;
Alkaline phosphatase for indigenous microbial activity;
Inhibition of β -galactosidase for indigenous microbial activity; and
Bacterial surrogate assay using O-nitrophenol- β -D-galactopyranside
activity and *Escherichia coli*.
3. EPA Environmental Research Laboratory, Duluth, MN
Ceriodaphnia dubia (water flea) 48-h survival; and
Pimephales promelas (fathead minnow) 96-h survival.
4. EPA Environmental Research Laboratory, Narragansett Bay, RI
Champia parvula (marine red alga) sexual reproduction (formation of cystocarps
after 5 to 7 d exposure); and
Arbacia punctulata (sea urchin) fertilization by sperm cells.

Table 4-18 summarizes the results of the toxicity tests. The *C. dubia*, *P. promelas*, and *C. parvula* tests experienced problems with the control samples and, therefore, these results are therefore uncertain. The *A. punctulata* tests on the stormwater samples also had a potential problem with the control samples. The CSO test results (excluding the fathead minnow tests) indicated that from 50% to 100% of the samples were toxic, with most tests identifying the same few samples as the most toxic. The toxicity tests for the stormwater samples indicated that 0% to 40% of the samples were toxic. The Microtox™ screening procedure gave similar rankings for the samples as the other toxicity tests.

Laboratory toxicity tests can result in important information on the effects of stormwater in receiving waters, but actual in-stream taxonomic studies should also be conducted. A recently published proceedings of a conference on stormwater impacts on receiving streams (Herrick 1995) contains many examples of actual receiving water impacts and toxicity test protocols for stormwater.

Table 4-18. Fraction of samples rated as toxic.

Sample series	Combined sewer overflows (%)	Stormwater (%)
Microtox™ marine bacteria	100	20
<i>C. Dubia</i>	60	0 ¹
<i>P. promelas</i>	0 ¹	0 ¹
<i>C. parvula</i>	100	0 ¹
<i>A. punctulata</i>	100	0 ¹
<i>D. magna</i>	63	40
<i>L. minor</i>	50 ¹	0

1) Results uncertain, see text

All of the Birmingham samples represented separate stormwater. However, as part of the Microtox™ evaluation, several CSO samples from New York City were also tested to compare the different toxicity tests. These samples were collected from six CSO discharge locations having the following land uses:

1. 290 acres, 90% residential and 10% institutional.
2. 50 acres, 100% commercial.
3. 620 acres, 20% institutional, 6% commercial, 5% warehousing, 5% heavy industrial, and 64% residential.
4. 225 acres, 13% institutional, 4% commercial, 2% heavy industrial. and 81% residential.
5. 400 acres, 1% institutional and 99% residential.
6. 250 acres, 88% commercial. 6% warehousing, and 6% residential.

Therefore, there was a chance that some of the CSO samples may have had some industrial process waters. However, none of the Birmingham sheetflow samples could have contained any process waters because of how and where they were collected.

The Microtox™ screening procedure gave similar toxicity rankings for the 20 samples as the conventional bioassay tests. It is also a rapid procedure (requiring about one hour) and only requires small (<1 ml) sample volumes. The Microtox™ toxicity test uses marine bioluminescence bacteria and monitors the light output for different sample concentrations. About one million bacteria organisms are used per sample, resulting in highly repeatable results. The more toxic samples produce greater stress on the bacteria test organisms that results in a greater light attenuation compared to the control sample. Note that the Microtox™ procedure was not used during this research to determine the absolute toxicities of the samples or to predict the toxic effects of stormwater runoff on receiving waters. It was used to compare the relative toxicities of

different samples that may indicate efficient source area treatment locations, and to examine changes in toxicity during different treatment procedures.

Potential Sources

A drainage system captures runoff and pollutants from many source areas, all with individual characteristics influencing the quantity of runoff and pollutant load.

Impervious source areas may contribute most of the runoff during small storm events (e.g., paved parking lots, streets, driveways, roofs, and sidewalks). Pervious source areas can have higher material washoff potentials and become important contributors for larger storm events when their infiltration rate capacity is exceeded (e.g., gardens, bare ground, unpaved parking areas, construction sites, undeveloped areas). Many other factors also affect the pollutant contributions from source areas, including: surface roughness, vegetative cover, gradient and hydraulic connections to a drainage system; rainfall intensity, duration, and antecedent dry period; and pollutant availability due to direct contamination from local activities, cleaning frequency/efficiency, and natural and regional sources of pollutants. The relative importance of the different source areas is therefore a function of the area characteristics, pollutant washoff potential, and the rainfall characteristics (Pitt 1987).

Important sources of toxicants are often related to the land use (e.g., high traffic capacity roads, industrial processes, and storage area) that are unique to specific land uses activities. Automobile related sources affect the quality and quantity of road dust particles through gasoline and oil drips/spills, deposition of exhaust products, and wear of tire, brake, and pavement materials (Shaheen 1975). Urban landscaping practices potentially produce vegetation cuttings and fertilizer and pesticide washoff. Miscellaneous sources include holiday firework debris, wildlife and domestic pet wastes, and possible sanitary wastewater infiltration. In addition, resuspension and deposition of pollutants/particles via the atmosphere can increase or decrease the contribution potential of a source area (Pitt and Bozeman 1982, Bannerman et al. 1993).

Results

Table 4-19 summarizes the source area sample data for the most frequently detected organic toxicants and for all of the metallic toxicants analyzed. The organic toxicants analyzed, but not reported, were generally detected in five, or less, of the non-filtered samples and in none of the filtered samples. Table 4-19 shows the mean, maximum, and minimum concentrations for the detected toxicants. Note that these values are based only on the observed concentrations. They do not consider the non-detectable conditions. Mean values based on total sample numbers for each source area category would therefore result in much lower concentrations. The frequency of detection is therefore an important consideration when evaluating organic toxicants. High detection frequencies for the organics may indicate greater potential problems than infrequent high concentrations.

Table 4-19 also summarizes the measured pH and SS concentrations. Most pH values were in the range of 7.0 to 8.5 with a low of 4.4 and a high of 11.6 for roof and concrete

plant storage area runoff samples, respectively. This range of pH can have dramatic effects on the speciation of the metals analyzed. The SS concentrations were generally less than 100 mg/l, with impervious area runoff (e.g., roofs and parking areas) having much lower SS concentrations and turbidities compared to samples obtained from pervious areas (e.g., landscaped areas).

Out of more than 35 targeted compounds analyzed, 13 were detected in more than 10% of all samples, as shown in Table 4-19. The greatest detection frequencies were for 1,3-dichlorobenzene and fluoranthene, which were each detected in 23% of the samples. The organics most frequently found in these source area samples (i.e., polycyclic aromatic hydrocarbons (PAH), especially fluoranthene and pyrene) were similar to the organics most frequently detected at outfalls in prior studies (EPA 1983a).

Roof runoff, parking area and vehicle service area samples had the greatest detection frequencies for the organic toxicants. Vehicle service areas and urban creeks had several of the observed maximum organic compound concentrations. Most of the organics were associated with the non-filtered sample portions, indicating an association with the particulate sample fractions. The compound 1,3-dichlorobenzene was an exception, having a significant dissolved fraction.

In contrast to the organics, the heavy metals analyzed were detected in almost all samples, including the filtered sample portions. The non-filtered samples generally had much higher concentrations, with the exception of zinc, which was mostly associated with the dissolved sample portion (i.e., not associated with the SS). Roof runoff generally had the highest concentrations of zinc, probably from galvanized roof drainage components, as previously reported by Bannerman et al. (1983). Parking and storage areas had the highest nickel concentrations, while vehicle service areas and street runoff had the highest concentrations of cadmium and lead. Urban creek samples had the highest copper concentrations, which were probably due to illicit industrial connections or other non-stormwater discharges.

Table 4-20 shows the relative toxicities of the collected stormwaters. A wide range of toxicities was found. About 9% of the non-filtered samples were considered highly toxic using the Microtox™ toxicity screening procedure. About 32% of the samples were moderately toxic and about 59% were considered non-toxic. The greatest percentage of samples considered the most toxic were from industrial storage and parking areas. Landscaped areas also had a high incidence of highly toxic samples (presumably due to landscaping chemicals) and roof runoff had some highly toxic samples (presumably due to high zinc concentrations). Treatability study activities indicated that filtering the samples through a range of fine sieves and finally a 0.45µm filter consistently reduced sample toxicities. The chemical analyses also generally found much higher toxicant concentrations in the non-filtered sample portions, compared to the filtered sample portions.

Table 4-19. Stormwater toxicants detected in at least 10% of the source area sheetflow samples (µg/l, unless otherwise noted).

	Roof areas		Parking areas		Storage areas		Street runoff		Loading docks		Vehicle service areas		Landscaped areas		Urban creeks		Detention ponds	
	NF. ¹	F. ²	NF.	F.	NF.	F.	NF.	F.	NF.	F.	NF.	F.	NF.	F.	NF.	F.	NF.	F.
Total samples	12	12	16	16	8	8	6	6	3	3	5	5	6	6	19	19	12	12
Base neutrals (detection limit = 0.5 mg/l)																		
1,3-Dichlorobenzene detection frequency = 20% N.F. and 13% F.																		
No. detected ³		2	3	2	1	1	1	1	0	0	3	2	3	2	2	0	1	1
Mean ⁴	52	20	34	13	16	14	5.4	3.3			48	26	29	5.6	93		27	21
Max.	88	23	103	26							72	47	54	7.5	120			
Min. ⁵	14	17	3.0	2.0							6.0	4.9	4.5	3.8	65			
Fluoranthene detection frequency = 20% N.F. and 12% F.																		
No. detected	3	2	3	2	1	0	1	1	0	0	3	2	3	2	1	0	2	1
Mean	23	9.3	37	2.7	4.5	0	0.6	0.5			39	3.6	13	1.0	130		10	6.6
Max.	45	14	110	5.4							53	6.8	38	1.3			14	
Min.	7.6	4.8	3.0	2.0							0.4	0.4	0.7	0.7			6.6	
Pyrene detection frequency = 17% N.F. and 7% F.																		
No. detected	1	0	3	2	1	0	1	1	0	0	3	2	2	0	1	0	2	1
Mean	28		40	9.8	8		1.0	0.7			44	4.1	5.3		100		31	5.8
Max.			120	20							51	7.4	8.2				57	
Min.			3.0	2.0							0.7	0.7	2.3				6.0	
Benzo(b)fluoranthene detection frequency = 15% N.F. and 0% F.																		
No. detected	4	0	3	0	0	0	1	0	0	0	2	0	1	0	2	0	0	0
Mean	76		53				14				98		30		36			
Max.	260		160								110				64			
Min.	6.4		3.0								90				8.0			
Benzo(k)fluoranthene detection frequency = 11% N.F. and 0% F.																		
No. detected	0	0	3	0	0	0	1	0	0	0	2	0	1	0	2	0	0	0
Mean			20				15				59		61		55			
Max.			1								103				78			
Min.			3.0								15				31			
Benzo(a)pyrene detection frequency = 15% N.F. and 0% F.																		
No. detected	4	0	3	0	0	0	1	0	0	0	2	0	1	0	2	0	0	0
Mean	99		40				19				90		54		73			
Max.	300		120								120				130			
Min.	34		3.0								60				19			

Table 4-19. Stormwater toxicants detected in at least 10% of the source area sheetflow samples (µg/l, unless otherwise noted).Continued.

	Roof areas		Parking areas		Storage areas		Street runoff		Loading docks		Vehicle service areas		Landscaped areas		Urban creeks		Detention ponds	
	NF. ¹	F. ²	NF.	F.	NF.	F.	NF.	F.	NF.	F.	NF.	F.	NF.	F.	NF.	F.	NF.	F.
Total samples	12	12	16	16	8	8	6	6	3	3	5	5	6	6	19	19	12	12
Bis(2-chloroethyl) ether detection frequency = 12% N.F. and 2% F.																		
No. detected		1	2	0	0	0	1	0	0	0	1	1	1	0	1	0	1	0
Mean	42	17	20				15				45	23	56		200		15	
Max.	87	2	39															
Min.	20		2.0								6.0	4.9	4.5	3.8	65			
Bis(chloroisopropyl) ether detection frequency = 13% N.F. and 0% F.																		
No. detected	3	0	3	0	0	0	0	0	0	0	2	0	1	0	2	0	0	0
Mean	99		130								120		85		59			
Max.	150		400								160				78			
Min.	68		3.0								74				40			
Naphthalene detection frequency = 11% N.F. and 6% F.																		
No. detected	2	0	1	1	0	0	0	0	0	0	2	1	1	0	1	1	2	2
Mean	17		72	6.6							70	82	49		300	6.7	43	12
Max.	21										100						68	17
Min.	13										37						18	6.6
Benzo(a)anthracene detection frequency = 10% N.F. and 0% F.																		
No. detected	1	0	3	0	0	0	0	0	0	0	2	0	1	0	1	0	0	0
Mean	16		24								35		54		61			
Max.			73								39							
Min.			3.0								31							
Butylbenzyl phthalate detection frequency = 10% N.F. and 4% F.																		
No. detected	1	0	2	1	0	0	0	0	0	0	2	2	1	0	1	0	1	0
Mean	100		12	3.3							26	9.8	130		59		13	
Max.			21								48	16						
Min.			3.3								3.8	3						
Pesticides (detection limit = 0.3 mg/l)																		
Chlordane detection frequency = 11% N.F. and 0% F.																		
No. detected	2	0	2	0	3	0	1	0	0	0	1	0	0	0	0	0	0	0
Mean	1.6		1.0		1.7		0.8											
Max.	2.2		1.2		2.9													
Min.	0.9		0.8		1.0													

Table 4-19. Stormwater toxicants detected in at least 10% of the source area sheetflow samples (µg/l, unless otherwise noted).Continued.

	Roof areas		Parking areas		Storage areas		Street runoff		Loading docks		Vehicle service areas		Landscaped areas		Urban creeks		Detention ponds	
	NF. ¹	F. ²	NF.	F.	NF.	F.	NF.	F.	NF.	F.	NF.	F.	NF.	F.	NF.	F.	NF.	F.
Total samples	12	12	16	16	8	8	6	6	3	3	5	5	6	6	19	19	12	12
Metals (detection limit = 1 µg/l)																		
Lead detection frequency = 100% N.F. and 54% F. No. detected		1	16	8	8	7	6	4	3	1	5	2	6	1	19	15	12	8
Mean	41	1.1	46	2.1	105	2.6	43	2.0	55	2.3	63	2.4	24	1.7	20	1.4	19	1.0
Max.	170		130	5.2	330	5.7	150	3.9	80		110	3.4	70		100	1.6	55	1.0
Min.	1.3		1.0	1.2	3.6	1.6	1.5	1.1	25		27	1.4	1.4		1.4	<1	1	<1
Zinc detection frequency = 99% N.F. and 98% F. No. detected	12	12	16	16	8	7	6	6	2	2	5	5	6	6	19	19	12	12
Mean	250	220	110	86	1730	22	58	31	55	33	105	73	230	140	10	10	13	14
Max.	1580	1550	650	560	13100	100	130	76	79	62	230	230	1160	670	32	23	25	25
Min.	11	9	12	6	12	3.0	4.0	4.0	31	4.0	30	11	18	18	<1	<1	<1	<1
Copper detection frequency = 98% N.F. and 78% F. No. detected	11	7	15	13	8	6	6	5	3	2	5	4	6	6	19	17	12	8
Mean	110	2.9	116	11	290	250	280	3.8	22	8.7	135	8.4	81	4.2	50	1.4	43	20
Max.	900	8.7	770	61	1830	1520	1250	11	30	15	580	24	300	8.8	440	1.7	210	35
Min.	1.5	1.1	10	1.1	10	1.0	10	1.0	15	2.6	1.5	1.1	1.9	0.9	<1	<1	0.2	<1
Aluminum detection frequency = 97% N.F. and 92% F. No. detected	12	12	15	15	7	6	6	6	3	1	5	4	5	5	19	19	12	12
Mean	6850	230	3210	430	2320	180	3080	880	780	18	700	170	2310	1210	620	190	700	210
Max.	71300	1550	6480	2890	6990	740	10040	4380	930		1370	410	4610	1860	3250	500	1570	360
Min.	25	6.4	130	5.0	180	10	70	18	590		93	0.3	180	120	<5	<5	<5	<5
Cadmium detection frequency = 95% N.F. and 69% F. No. detected	11	7	15	9	8	7	6	5	3	3	5	3	4	2	19	15	12	9
Mean	3.4	0.4	6.3	0.6	5.9	2.1	37	0.3	1.4	0.4	9.2	0.3	0.5	0.6	8.3	0.2	2	0.5
Max.	30	0.7	70	1.8	17	10	220	0.6	2.4	0.6	30	0.5	1	1	30	0.3	11	0.7
Min.	0.2	0.1	0.1	0.1	0.9	0.3	0.4	0.1	0.7	0.3	1.7	0.2	0.1	0.1	<0.1	<0.1	0.1	0.4
Chromium detection frequency = 91% N.F. and 55% F. No. detected	7	2	15	8	8	5	5	4	3	0	5	1	6	5	19	15	11	8
Mean	85	1.8	56	2.3	75	11	9.9	1.8	17		74	2.5	79	2.0	62	1.6	37	2.0
Max.	510	2.3	310	5.0	340	32	30	2.7	40		320		250	4.1	710	4.3	230	3.0
Min.	5.0	1.4	2.4	1.1	3.7	1.1	2.8	1.3	2.4		2.4		2.2	1.4	<0.1	<0.1	<0.1	<0.1

Table 4-19. Stormwater toxicants detected in at least 10% of the source area sheetflow samples (µg/l, unless otherwise noted).Continued.

	Roof areas		Parking areas		Storage areas		Street runoff		Loading docks		Vehicle service areas		Landscaped areas		Urban creeks		Detention ponds	
	NF. ¹	F. ²	NF.	F.	NF.	F.	NF.	F.	NF.	F.	NF.	F.	NF.	F.	NF.	F.	NF.	F.
Total samples	12	12	16	16	8	8	6	6	3	3	5	5	6	6	19	19	12	12
Nickel detection frequency = 90% N.F. and 37% F.																		
No. detected		0	14	4	8	1	5	0	3	1	5	1	4	1	18	16	11	8
Mean	16		45	5.1	55	87	17		6.7	1.3	42	31	53	2.1	29	2.3	24	3.0
Max.	70		130	13	170		70		8.1		70		130		74	3.6	70	6.0
Min.	2.6		4.2	1.6	1.9		1.2		4.2		7.9		21		<1	<1	1.5	<1
Other constituents (always detected, analyzed only for non-filtered samples)																		
pH																		
Mean	6.9		7.3		8.5		7.6		7.8		7.2		6.7		7.7		8.0	
Max.	8.4		8.7		12		8.4		8.3		8.1		7.2		8.6		9.0	
Min.	4.4		5.6		6.5		6.9		7.1		5.3		6.2		6.9		7.0	
Suspended solids																		
Mean	14		110		100		49		40		24		33		26		17	
Max.	92		750		450		110		47		38		81		140		60	
Min.	0.5		9.0		5.0		7.0		34		17		8.0		5.0		3.0	

1) N.F.: concentration associated with a nonfiltered sample.

2) F.: concentration after the sample was filtered through a 0.45 µm membrane filter.

3) Number detected refers to the number of samples in which the toxicant was detected.

4) Mean values based only on the number of samples with a definite concentration of toxicant reported (not on the total number of samples analyzed).

5) The minimum values shown are the lowest concentration detected, they are not necessarily the detection limit.

Replicate samples were collected from several source areas at three land uses during four different storm events to statistically examine toxicity and pollutant concentration differences due to storm and site conditions. These data indicated that variations in Microtox™ toxicities and organic toxicant concentrations may be partially explained by rain characteristics. As an example, high concentrations of many of the PAHs were associated with long antecedent dry periods and large rains (Barron 1990).

Table 4-20. Relative toxicity of samples using Microtox™ (non-filtered).

Local Source Areas	Highly Toxic (%)	Moderately Toxic (%)	Not Toxic (%)	Number of Samples
Roofs	8	58	33	12
Parking Areas	19	31	50	16
Storage Areas	25	50	25	8
Streets	0	67	33	6
Loading Docks	0	67	33	3
Vehicle Service Areas	0	40	60	5
Landscaped Areas	17	17	66	6
Urban Creeks	0	11	89	19
Detention Ponds	8	8	84	12
All Areas	9	32	59	87

Microbics suggested toxicity definitions for 35 minute exposures:

Highly toxic - light decrease >60%

Moderately toxic - light decrease <60% & >20%

Not toxic - light decrease <20%

References

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